AD-A176 079 FEASIBILITY STUDY OF CONCEPTS LEADING TO SIMPLIFIED FUEL CONTROLS FOR NAVAL AIR PROPULSION CENTER(U) CHANDLER EVANS INC WEST HARTFORD CT CONTROL SYSTEMS DIV 1/1

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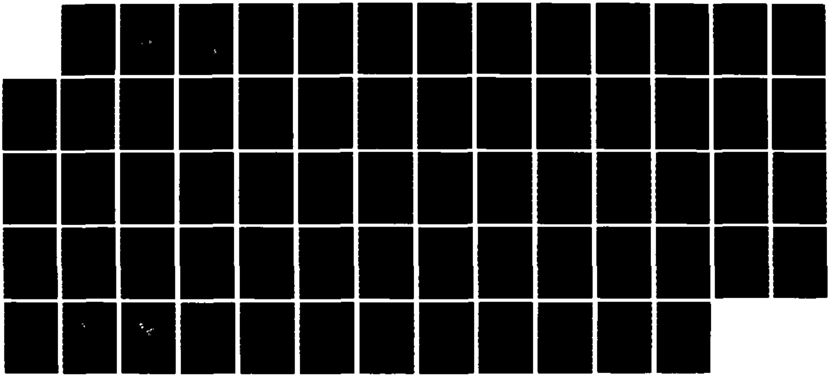

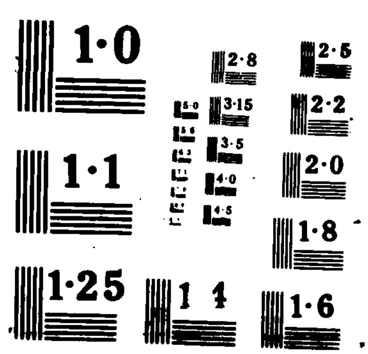
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AD-A176 079

FINAL REPORT

FEASIBILITY STUDY OF CONCEPTS

LEADING TO

SIMPLIFIED FUEL CONTROLS

FOR

NAVAL AIR PROPULSION CENTER

Chandler Evans

Control Systems Division

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(2)

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FINAL REPORT

FEASIBILITY STUDY OF CONCEPTS LEADING TO SIMPLIFIED FUEL CONTROLS FOR NAVAL AIR PROPULSION CENTER

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ABSTRACT

Engine control systems state-of-the-art has progressed to the flight-weight demonstration of full authority electronic controls. However, aircraft carrier operations and future combat scenarios may subject electronic controls to increasing levels of EMI and EMP. As a result, even multi-engine weapon systems may lose their get-home capability due to the malfunction of the electronic main engine control.

In an effort to address this concern, a feasibility study was done on a hydromechanical implementation of a new control concept proposed by NAVAIR, aimed at providing a simple, versatile fuel control. The control features proportional-plus-integral control on speed error with variable gain. A simplification to this concept was made by a two straight line approximation to the variable gain function, which amounted to limiting the speed error sensed by the control to a specified maximum value.

The study centered around closed-loop computer simulations, utilizing available 600 SHP and 5000 SHP engine models, to investigate the characteristics and the performance of the speed error control. The results of the study show the speed error control to be a feasible means of gas turbine engine control. The major drawback to the control concept is the open-loop operation which results during a transient from the use of a speed error limiter. A revised speed error concept is also included which appears to solve the open-loop operation problem.

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1. INTRODUCTION

In recent years, Navy expenditures on research and development of gas turbine engine fuel controls have been almost totally concentrated on digital electronic controls. This has led to concern over the possible vulnerability of such controls in future EMI/EMP warfare. For this reason, the need has arisen for FADEC backup controls insensitive to EMI/EMP.

Current hydromechanical control technology using inlet temperature compensated Wf/P open-loop control is suitable for FADEC backup, but these systems are complicated and expensive. Moreover, scheduling controls lack flexibility in that any change to the desired Wf/P schedule normally requires hardware changes. Thus, schedule changes could prove more costly for the backup system than for the primary digital control system. NAVAIR personnel have also expressed concern over consistency and repeatability of open-loop schedules. Therefore, NAPC initiated this program to develop a simplified fuel control system that will provide FADEC backup with get-home capability, insensitive to EMI/EMP. A secondary goal is to provide a control which will allow mission completion.

The approach to meeting this goal is based on past preliminary development work by NAVAIR that included successful computer studies and engine demonstration testing of a simplified fuel control concept that uses a new control strategy. The control strategy provides isochronous control and can be described by the following equation.

$$Wf/P = (No - N)(N/No)^n (KP + KI/s)$$

where

Wf = fuel flow

P = pressure bias for altitude compensation

No = set speed

N = actual speed

n = constant

KP = proportional gain

KI = integral gain

The operation of the control is based on speed error. The $(No - N)$ term is the actual speed error. The $(N/No)^n$ term acts to reduce the control gain during large transients to prevent overfueling. The degree of gain reduction necessary can be accommodated by proper selection of the exponent n. The product of the two terms represents the speed error sensed by the control. A graph of this error function is provided in Figure 1. The function plots not as a single curve, but rather as a family of curves depending on what the set speed is; e.g., a 10% speed error at 70% speed would yield a different gain than a 10% speed error at 90% speed.

As a practical matter, this exponential speed error function does not lend itself to easy hydromechanical implementation. For this reason, it was suggested that this function can be simplified by a two straight line approximation. This is also shown in Figure 1. This straight line approximation gives evidence of the fundamental operation provided by this system; i.e., it represents limiting the speed error sensed by the control to a constant maximum value, hereafter referred to as the speed error limit.

One additional feature of the NAVAIR speed error control concept is that the control's proportional and integral actions have been physically separated to allow independent adjustment. This feature, along with adjustability of the error limit, not only facilitates engine trim but provides a universality of the control; the three control parameters can be adjusted to accommodate a wide variety of engine applications.

This control concept was successfully demonstrated by NAVAIR in 1980 on a TF30 engine computer simulation. Following this, an electronic "breadboard" of the concept was used to run a TF30 engine at NAPC. These tests showed the control's dynamic performance capabilities, and demonstrated equal performance with substitution of the straight line approximation for the original error function.

The following is a description of the study of this control concept, including findings and recommendations. The study is centered around a computer model of the speed error control concept, which is used in closed-loop computer simulations with two different engine models. In addition to investigating the feasibility of the control concept and studying its characteristics and limitations, a possible means of hydromechanical implementation of the control is included, as well as estimates of production cost, size, weight and system reliability.

2. TECHNICAL APPROACH

This program can be broken down into four basic phases. The first phase involved setting up a functional specification for the control, defining a baseline control against which to compare the proposed simplified control, and then developing the mathematical models - both baseline control and speed error control models - to be used. (The engine models used were in-house engine models.) The second phase amounted to investigating the characteristics of the speed error control, establishing the feasibility of the concept, and evaluating the performance of the control relative to a baseline scheduling control. The third phase involved preparing a schematic for hydromechanical implementation of the control and preliminary sizing of the components to confirm the feasibility of hydromechanical implementation. The fourth phase was an evaluation comparing the speed error control with a conventional Wf/P scheduling control baseline. The following sections describe the work done in each phase.

2.1 Functional Specification

A functional specification was prepared for the backup fuel control based on requirements for core engine control. These requirements include accelerating and decelerating the engine, steady-state governing, starting, and shutdown, all to be performed by the speed error control. Also required were the necessary FADEC interfaces. To establish the environmental operating requirements, the backup control system's performance envelope was based on a JVX engine application. Specifications for three MTE controls were reviewed for reference information. Figure 2 summarizes the control requirements for these engines. The MTE was selected because it originally was designated for use on the Navy JVX, thereby providing a real potential application for a backup control. As indicated in Figure 2, the

backup system is intended to provide only core engine control. Requirements for load sharing, temperature limiting and power turbine speed control are not needed for a backup get-home capability. Moreover, power turbine speed governing and load sharing are handled in JVX flight computers, and providing a hydromechanical backup control for these functions was beyond the requirements of this study. Variable geometry control would most likely be needed in a backup control system, and some consideration was given to devise a simplified hydromechanical geometry actuator control. As an additional consideration, since one of the potential advantages of this control concept was universality - being usable for a number of different engine applications - and MTE computer models were not available, two different size engines were used in the study, engines for which models were available in-house.

2.2 Baseline Control

Previous studies have been done on FADEC backup, including an AFAPL-funded program.* This effort included trade studies that considered electronic, fluidic and hydromechanical technologies to implement conventional control means. The work resulted in the selection of a conventional open-loop Wf/P hydromechnical control, ruling out electronics because of EMI/EMP and fluidics because of contamination problems and limitations in functional maturity, accuracy, and force levels. Because a conventional Wf/P scheduling control is seen as being a readily acceptable means of FADEC backup, it was selected as the baseline control for this study, providing a basis for comparison for dynamic performance, cost and reliability. Physically, the baseline control is a flyweight engine core speed governor with 3-D acceleration cam and mechnical pressure multiplier for altitude compensation.

(*) Kast, H. B., "Backup Control for a Variable Cycle Engine - Phase II Final Report", AFAPL-TR-79-2069, July 1980

2.3 Computer Models

Block diagrams for the two control computer models are provided in Figure 3. The simplified fuel control model represents the speed error control. In this model, the actual speed and set speed are subtracted to produce a speed error. If this speed error is less than the speed error limit, the proportional-plus-integral governor acts on this speed error, yielding a fuel ratio (Wf/P3) necessary to reduce the speed error. If the speed error is greater than the speed error limit, the value of the speed error limit is substituted for the actual speed error (with appropriate sign) and the proportional-plus-integral governor acts on speed error limit. The output fuel ratio is then multiplied by CDP and the resultant fuel flow is subjected to a first-order lag representing the overall fuel metering control lag.

The baseline control model contains a proportional-plus-integral governor acting on a speed error to generate a demanded fuel ratio. However, this demanded fuel ratio is then compared to the acceleration schedule for the particular engine and the lower of the two values is selected. The resultant selected fuel ratio is multiplied by CDP and then subjected to the same first-order control lag used in the speed error control model. This baseline control model was used to generate engine transient response data for the 600 SHP engine to be used in dynamic performance comparisons with the control. This was possible due to the simplicity of the control requirements for this engine. Baseline transient response data for the 5000 SHP engine was obtained from data already available for that engine. (It should be noted here that the control used in this engine data provided proportional control rather than isochronous control to which it will be compared.)

The engine model used is a standard torque balance model for an engine gas generator. A block diagram is provided in Figure 4. To evaluate the flexibility of the speed error control, two different engines were modeled and used in computer simulations. The first engine modeled was a small 600 SHP turboshaft engine, while the second engine used was a larger 5000 SHP engine, typical of the MTE. The differences between the engines, other than size, lie in the characteristics of their acceleration schedules. The standard day acceleration schedules for the 600 SHP and the 5000 SHP engines are provided in Figures 5 and 6, respectively. As can be seen from these figures, the acceleration schedule for the 600 SHP engine is a single constant fuel ratio; the steady-state operating curve and the acceleration schedule converge at about 110% speed. The acceleration schedule for the 5000 SHP engine is dependent on speed, and the schedule is approximately a constant number of ratio units away from the steady-state operating line. This difference is noteworthy because it led to certain conclusions about the speed error control.

Simulated engine transients were run on an HP-1000 digital computer for core engine speeds ranging from 70% speed to 100% speed. Flight conditions used represented the corners of the flight envelope, which are sea level to 30,000 feet, hot and cold day.

3. CONTROL DESIGN PARAMETERS

To determine the design characteristics of the speed error control, numerous transients were run with the computer simulation, and control gain/speed error limit combinations were established such that at no time would the fuel ratio requested by the control exceed the specified Wf/P3 acceleration schedule. The upper limit of these combinations, where the normal acceleration schedule would just be met but not exceeded, represented the optimal combinations. From these, a single combination would be selected, based on transient characteristics and error limit size.

The environmental conditions most likely to cause exceedance of the specified acceleration limit if control gains were set too high are high altitude/hot day. For this reason, gain/error limit combinations were selected by running 30% speed transients (70% to 100% speed) for engine inlet conditions simulating 30,000 feet, hot day (P1 = 4.37 psia, T1 = -6°F).

Figure 7 shows the relationship between control gains and the maximum allowable speed error limit for the 600 SHP engine. The figure shows a plot of speed error limit (expressed in percent of 100% speed) vs. control gain (KI) for constant values of control proportional gain (KP). Three major characteristics of the speed error control are observable from this graph. First is that the allowable speed error is quite small - here less than 2% speed. Second, the allowable speed error is inversely proportional to the control integral gain. Third, the control proportional gain has little effect on the allowable speed error. The latter two points actually result from the first. With a 30% speed transient and such a small speed error limit, the majority of the transient occurs while on the error limiter. Under these circumstances, the output of the control is just a

ramp in fuel ratio, the ramp being the integral of the speed error limit. It is this ramp in fuel ratio that accelerates the engine. To avoid overfueling the engine, fuel ratio must be increased at a rate which is related to the acceleration capabilities of the engine. This restricts the ramp in fuel ratio to a particular maximum rate. As this rate is the product of the control integral gain and the speed error limit, the two parameters share an inverse relationship. A higher integral gain will yield a very small speed error limit; a higher speed error limit will yield a low integral gain and consequently very long transient settling times. The combinations of integral gain and speed error limit shown in Figure 7 are those which are considered most reasonable with respect to error limit size and transient response.

In actuality, the first choice for control gains were those determined by a stability analysis on the system. However, the speed error limit resulting from this gain selection was extremely small and became obvious that if error limit size were to be a criterion in the gain selection process, then control gains representing stability limits would not be considered reasonable. Conversely, for those combinations deemed reasonable, system stability should not prove to be a problem.

Figures 8 and 9 show fuel ratio and speed for a 30% speed transient using a control gain/error limit combination taken from Figure 7. From this, the ramp in fuel ratio can be seen, as well as the initial proportional action. The point at which the ramp ends is when the actual speed error becomes less than the speed error limit.

The transient shown has engine inlet conditions representing high altitude, hot day. As can be seen, under these conditions the fuel ratio just reaches the normal acceleration schedule (also shown). Under sea level/standard conditions, the acceleration limit would not be reached as the engine would respond faster and the speed error would be reduced sooner.

The control gain/error limit combinations for the 5000 SHP engine are shown in Figure 10. The results for this engine correlate well with those for the smaller engine. The three characteristics pointed out earlier are also present here, speed error limits are in the 1% to 3% speed range, and the relationships between control integral gain, proportional gain, and speed error limit show the same pattern. Again, the gains and error limits have been restricted to reasonable values which exhibit relatively rapid small signal responses without excessively small speed error limits. And as before, control gains are well below stability limits.

One drawback to the use of a speed error limiter is that whenever the actual speed error exceeds the error limit and the limiter is in effect, the actual speed feedback to the governor is essentially cut off and the control loop is broken, resulting in temporary open-loop operation until the speed error is reduced. The smaller the speed error limit, the more frequently the system operates open-loop. Open-loop operation reduces the control's ability to compensate for system disturbances. For example, due to the control's open-loop operation, an increase in fuel heating value would not be compensated for by the control and overfueling of the engine could result. To design a 10% loop gain margin into the control would require approximately a 10% decrease in speed error limit, on an error limit which is already considered quite small. Therefore, large speed error

limits are desirable to provide more continuous closed-loop operation, hopefully without sacrificing control gains and small signal response. In an effort to find methods of accomplishing this increase in speed error limit, the use of ambient air pressure (P1) for altitude compensation was also studied.

The control model was modified to utilize a P1 multiplier and the gain/error limit selection process was repeated for the 600 SHP engine. (Although the control is this model uses P1 for altitude compensation, the transient relationship between Wf and P3, as compared to the engine Wf/P3 acceleration schedule, is still used as the basis for the selection of control gain/speed error limit combinations.) It was found that the allowable speed error limits were higher when using P1 biasing, but the difference amounted to only about 2% speed. However, the engine transient characteristics turned out to be quite different. Control output using P1 biasing results in a ramp in fuel flow rather than fuel ratio. As the engine begins to accelerate, the increase in speed will bring with it a corresponding increase in P3. By selecting appropriate control gains and speed error limit, fuel flow can be ramped at a rate such that P3 increases at about the same rate, keeping fuel ratio relatively constant during the transient. With an acceleration schedule consisting of a constant fuel ratio, the P1 biased speed error control very closely approximates the baseline scheduling control for large transients. Figure 11 shows fuel ratio vs. engine speed for a 30% speed change using P1 biasing on the 600 SHP engine. As can be seen, fuel ratio remains relatively constant throughout the transient.

Although the P1 biased system responded to large speed changes faster than the P3 biased system, its performance is lacking in other areas. First, and most importantly, P3 biasing provides inherent surge protection for the engine. If the engine begins to surge, P3 will drop which, through the control multiplier, will cause a drop in fuel flow, helping the engine to recover. The P1 biased system does not provide this protection.

Second, using a P3 multiplier in the control has the effect of increasing the control gain (in PPH per % speed) at high speeds where the engine is less sensitive to changes in fuel flow. In this manner, the open-loop gain of the system is relatively insensitive to changes in engine speed, and better small signal response and stability are achieved for the entire range of speeds. P1 biasing offers only altitude gain compensation, and small signal response at high speeds is considerably slower.

It was also found that the usefulness of P1 for altitude compensation is not universal. The shape of the acceleration limit influences its usefulness. In the case of an engine with an acceleration limit consisting of a constant fuel ratio, P1 biasing can be advantageous - at least for large transients - as was just shown. However, an engine with an acceleration limit that increases with engine speed, as with the 5000 SHP engine model, a normal scheduled engine acceleration is more closely approximated with P3 biasing where fuel ratio is ramped. An example of this on the 5000 SHP engine is provided in Figure 12. In such a case, P1 biasing can cause excessive response times for large transients. For this reason, P3 biasing was selected as the method of altitude compensation for this study.

In a further effort to increase the speed error limit, the original control function (Figure 1) was tried, as possibly some advantage had been diminished because a straight line approximation had been used. This system performed effectively the same as the straight line approximation, and although the system using the original function operates closed-loop continuously, loop gains and actual speed error impose the same limitations as does the straight line approximation.

At this point, final values of control gains and speed error limits were selected for each engine for use in dynamic performance comparisons. Gains were selected predominantly on the basis of small signal response. Because of the inverse relationship between control gain and speed error limit, the choice of gain/error limit combination has little effect on large transient response. For this reason, small signal response and size of the speed error limit were the criteria in the selection.

Neglecting the control time lag, the gain of the simplified control (when not on the error limiter) is:

$$G = KI/s + KP$$

By factoring out the KI/s term from the right side of the equation, we get:

$$G = KI/s(1 + KP/KI \times s)$$

This is merely an integrator with gain KI and a first-order lead with a time constant equal to KP/KI. Normally, KI and KP are selected such that this time constant cancels the engine lag time constant. This is, in fact, what was done on the 5000 SHP engine. However, on the 600 SHP engine, this process yielded excessively small speed error limits, so a compromise was made between desired dynamics and speed error limit.

The gains and speed error limits selected for each engine are:

Engine	KI (PPH/psi/sec/%N)	KP (PPH/psi/%N)	Error Limit (%N)
600 SHP	.120	.280	1.42
5000 SHP	.850	.476	1.71

4. SYSTEM PERFORMANCE COMPARISON

Having established the feasibility of the speed error control and selected appropriate control parameters, dynamic performance comparisons were conducted between the two speed error control systems and their respective baseline systems. For the 600 SHP engine system, comparisons were made for a number of different speed changes at both sea level and high altitude. Comparison runs were made with the 5000 SHP engine system only of the transients for which there were available baseline data.

Comparison transient responses for the 600 SHP engine system are provided in Figures 13 through 17. The speed error control is considerably slower than the baseline for large transients, requiring about twice as long to complete a 30% speed change regardless of altitude. The slower response is due to ramping fuel ratio on an engine with a constant fuel ratio acceleration schedule. Much of the engine's capacity for additional fuel flow goes unused, capacity that is utilized by the baseline system. The relative performance of the speed error control improves as the size of the speed change decreases. For small speed changes, the speed error control responds more like the baseline control. One noticeable difference between the two in the traces shown is the lack of any significant speed overshoots by the speed error control. This is due to the large lead time constant of the control, which was required for proper large transient response, relative to the baseline (almost three times as large).

Comparative transient responses for the 5000 SHP engine system are provided in Figures 18 through 21. Here there is much more similarity between the speed error control and the baseline, even for large transients. (The similarity in large transient responses is not surprising in light of the similarity between the control output and the normal engine acceleration schedule.) A 30% speed change takes the speed error control only 0.7 seconds longer to complete than the baseline control. However, whereas the baseline system overshoots the final speed by approximately 3% speed, the speed error control reduces this overshoot to less than 1% speed. For smaller transients, the speed error control requires only 0.1 to 0.4 seconds longer to complete the transient. In addition, the system dynamics; i.e., the size and shape of any overshoots, are much more similar, a result of having been able to match the time constant of the control with the engine.

Both speed error control systems respond rapidly to small speed changes, relative to their respective baselines. This is desirable for steady state governing to prevent drifting of limit cycling. The major discrepancy occurs with large transients on the 600 SHP engine, where the speed error system takes up to 2-3 seconds longer to accelerate the core engine. It can be argued that a three-second difference in core engine acceleration time will have little effect on the maneuverability of the aircraft (although helicopter applications may require rapid accelerations to prevent rotor speed undershoots). However, the longer acceleration times do not appear to be an inherent characteristic of the speed error control, but rather depend on the nature of the engine acceleration schedule.

5. HYDROMECHANICAL IMPLEMENTATION

A schematic for hydromechanical implementation of the speed error control is provided in Figure 22. The system shown provides proportional-plus-integral control of a limited speed error, with appropriate gain adjustments, and also contains a possible means of interfacing with a primary FADEC unit.

A speed error signal is generated by a comparison of the flyweight force with a reference force provided by the input servo and speeder spring. The result is a flyweight position proportional to the speed error. The speed error is limited by restricting the movement of the output linkage. This limited error signal operates a proportional follow-up servo which provides sufficient force to operate the rest of the control linkages without affecting the force balance on the flyweights. The lever between the flyweights and the proportional servo contains a movable pick-up point which allows adjustment of the overall control gain. The speed error limit stops are also adjustable.

The output of the proportional servo provides the proportional action of the controller through an appropriate linkage ratio. This linkage also provides an input to the integrator by operating a bleed valve. The position of the wiper arm controls the rate of movement of the integrator servo piston and, thereby, the motion of this piston is the integral of the speed error. The proportional output and the integrator output are added together and their sum becomes the position of the summing link. This position represents the fuel ratio demanded by the controller. The demanded fuel ratio is input to the multiplier linkage.

A P3 pressure sensor, which consists of a bellows actuated servo, provides the other input to the multiplier linkage. A force balance between an evacuated bellows and a bellows supplied by engine compressor discharge pressure, P3, operates a flapper valve. If P3 increases, it forces the flapper off null, porting servo pressure to drain. The servo moves down until the feedback force from the attached spring brings the flapper back to null. A decrease in P3 causes the flapper to block servo flow and increase the backpressure on the servo piston, moving the piston until it renulls the flapper. The result is a servo position proportional to P3. This linear position and the speed controller's angular position output are mechanically mutliplied to yield a fuel valve position.

Fuel metering components consist of a contaminant resistant flat plate metering valve and a standard metering head valve and pressurizing valve - all standard CECO designs. The servos in this schematic all operate using a supply pressure which is held at a constant value above drain pressure by a supply pressure regulator. This keeps the servos from being sensitive to operating pressure levels.

The requested engine speed is a function of the reference force provided to the speed error sensor by the power lever input servo. This servo converts the power lever rotary position to a servo piston position through a PLA driven rotary profile valve. During operation of the backup system, servo supply pressure is applied to the servo. The power lever operates a rotary profile cam, and this cam profile varies the effective area of a hole in the servo piston. This area acts as the downstream restrictor of two in series to produce a control pressure. The pressure between the two restrictors then acts on the servo piston and translates it to a position which brings the pressure forces on the piston back to equilibrium.

Also included in this system is a mechanism for use in manual engine starts. This mechanism allows the scheduling of Wf/P3 as a function of power lever by taking control of the integrator piston via a position feedback linkage. It comes into play when the power lever is set below idle. At these positions, the reference force on the flyweights is low and the linkage will move up against the error limit stop (aided by the loading spring in the proportional servo). The proportional servo will move up, causing the integrator input link to back off and allow its loading spring to close the bleed valve. With the bleed closed, the integrator servo will slew up until it comes into contact with the power lever operated feedback linkage. Further movement of the servo will lift the feedback link, which is connected to the bleed valve wiper arm, thus opening the bleed valve. When the valve reaches null, the servo will stop moving. (If the power lever is set at zero degrees, this would occur at a position corresponding to a fuel ratio of zero.) The integrator servo is now a proportional device, the servo position being proportional to the power lever cam radius. If the cam radius increases, the linkage will open up the bleed valve causing the servo to move down to a higher fuel ratio until the valve reaches null again. The opposite would occur for a cam radius decrease.

Additional hardware is included to provide for primary/backup changeover. This hardware amounts to a solenoid operated primary/backup changeover servo, a changeover valve, and appropriate interfacing to allow the primary system to share fuel metering hardware with the backup control.

In the primary mode, the solenoid in the changeover servo will be energized, porting drain pressure to two other servos. One of these servos provides the reference force on the flyweights along with an input from the power lever servo. With drain pressure ported to this servo, the speeder spring is unloaded and the flyweights will move up against the error limit stop. This provides a known reference position for the backup control linkage and, in particular, the pivot point of the backup summing link (the normal input point for the backup proportional action). The second servo operates a three-way valve, giving control of the integrator to the primary system. (Having both systems operate through the integrator piston is important as it provides proper positioning of the piston prior to changeover. This minimizes any necessary excursion of the piston during changeover, thus minimizing engine transients resulting from primary/backup changeover.) A stepper motor and gearhead provide the primary system's input to the hydromechanical fuel metering unit by modulating the backpressure on the integrator piston to position the piston for the desired fuel ratio. Position feedback to the control electronics is provided by a resolver on the fuel ratio lever. Proportional control of the stepper would be done through counting steps.

During changeover, the solenoid is energized, porting supply pressure to the two servos. This moves the speeder spring servo to a position determined by the power lever shaft position, thereby providing the proper reference force for the speed error sensor. Supply pressure also switches the three-way valve, giving control of the integrator to the backup system. (NOTE: While in backup mode, the stepper motor is deenergized.) The remainder of the system will operate as previously described.

Preliminary calculations have been done in sizing the components shown here to insure that a future hardware design of this configuration is practical. These calculations yielded reasonable component sizes and did not indicate any problems in system implementation.

Although the subject of variable geometry control was not addressed in the computer simulations, it was planned to include variable geometry in this schematic. Geometry is normally scheduled according to corrected core speed, requiring a tachometer, a temperature input and a 3-D cam. If this method were used, all of the elements for a scheduling control would be present and this would no longer be a simple, low cost control. Surrogates for corrected core speed, such as compressor pressure ratio or approximating corrected speed with temperature biased speed, were studied but there was no available information on the required accuracy of geometry scheduling. Without such accuracy requirements, the feasibilty of any surrogate cannot be properly assessed. The study of variable geometry accuracy requirements is a subject in itself and is beyond the scope of this study. Without sufficient information, the subject has been left open.

6. DESIGN ASSESSMENT

The design assessment portion of this study is aimed at evaluating the physical characteristics of the speed error control and determining quantitatively any cost or reliability advantages of the control concept. Estimates were made by comparing the hardware necessary to implement the concept with that of a baseline Wf/P scheduling control. To do this, a CECO production hydromechanical control was selected as a typical Wf/P scheduling control, providing cost and reliability baselines. This was done by comparing the hardware necessary to implement the concept with that of a baseline Wf/P scheduling control.

The baseline Wf/P scheduling control is shown schematically in Figure 23. It consists of a throttle lever input, speed sensor, temperature sensor, 3-D cam, lowest wins (acceleration, deceleration or governor) rockshaft linkage, pressure sensor/servo and multiplier linkage. The fuel metering portion of the baseline control is not shown here. It is felt that no significant difference exists between the fuel metering components of the baseline control and the speed error control. In addition, parts associated with primary/backup changeover are ignored as they are considered common to both systems.

A production cost comparison of the two systems was performed by comparing schematics of the two controls, eliminating common components based on function and complexity, and pricing the remaining parts. Figure 24 shows those parts from the baseline control which are not common to both controls (common parts are shaded out). Therefore, the components not common to both controls; i.e., those

eliminated by changing from a scheduling control to a speed error control, consist of the temperature sensor and associated bellows, a 3-D cam and a rockshaft linkage. The parts eliminated were then priced. In addition, the cost associated with machining the main castings in the control were adjusted to reflect the reduction in part count. A final cost was then calculated for a lot of 100 baseline units with and without the parts not common to both controls. The total cost reduction for the speed error control amounted to 16%.

Estimates of the size and weight of the speed error control were made based upon figures for present controls with similar hardware, along with basic experience in fuel control design. The component sizes determined to assure design practicality were also utilized in the estimates. Fuel metering hardware (metering valve, head regulator and pressurizing valve) was also included in the estimates, as was all changeover hardware appearing in the schematic in Figure 22 (solenoid, stepper motor, changeover valve, etc.). The estimated weight and volume figures are:

Estimated Weight	13 lbs.
Estimated Volume (Actual)	162 cu. in.
Estimated Volume (Envelope)	225 cu. in.

An overall control reliability estimate was calculated in a manner similar to the cost estimate. A failure rate for the baseline control was adjusted for the parts eliminated and a failure rate for the speed error control was thereby determined. The most significant change in the parts affecting reliability was the elimination of the temperature sensor, which resulted in removing two bellows from the baseline system. In addition, a number of springs were eliminated by the system. With the parts eliminated and using presently available reliability information, the overall failure rate is reduced 26% by changing to the speed error control.

7. SUMMARY AND RECOMMENDATIONS

The speed error control concept has been shown to be a feasible means of controlling gas turbine engine speed without the use of fuel scheduling. In this study, it has been shown, through computer simulations, to be capable of accelerating the engine from idle to 100% speed without overfueling, as well as governing steady state speed. In other studies, it has successfully run a TF30 engine in computer simulations, as well as in actual engine demonstration testing. In addition, the use of separate gain adjustment adds a flexibility to the control that would make the same unit compatible with a number of different engines. However, in the course of this study, certain performance limitations have emerged which will be discussed and summarized here.

The greatest drawback to the speed error control is open-loop operation during most transients. Through the control gain/error limit selection process, the optimal combinations of these parameters resulted in speed error limits in the 1-2% range. This means that for nearly any situation other than steady state governing, temporary open-loop system operation will result. This is equivalent to open-loop rate limiting the control output. Large speed changes will almost totally take place open-loop. Consequently, any disturbances to the system during a transient, or any change which might cause the open-loop gain to increase (for example, metering head or fuel heating value) will go unnoticed and uncorrected by the control, and the control output will go unchanged. To anticipate disturbances and design gain margins into the control results in substantial increases in transient response times.

The other major problem is associated with altitude compensation. Although the control is altitude compensated steady state, it is not dynamically. This is exemplified by the fact that the control gain/error limit characteristics are determined at the high altitude condition. For the control to be dynamically altitude compensated, the integrator slew rate would have to decrease with ambient pressure to match the engine's decreased responsiveness. If gains and error limits were selected at sea level, integrator wind-up and overfueling would result at high altitudes. Conversely, selecting gains and error limits for high altitude results in less than optimal performance at sea level.

In an effort to alleviate these problems, a variation on this speed error control has been devised with these two particular areas in mind. The two major changes are as follows:

1. The error limit has been moved outside of the control loop and now acts only on the input signal.

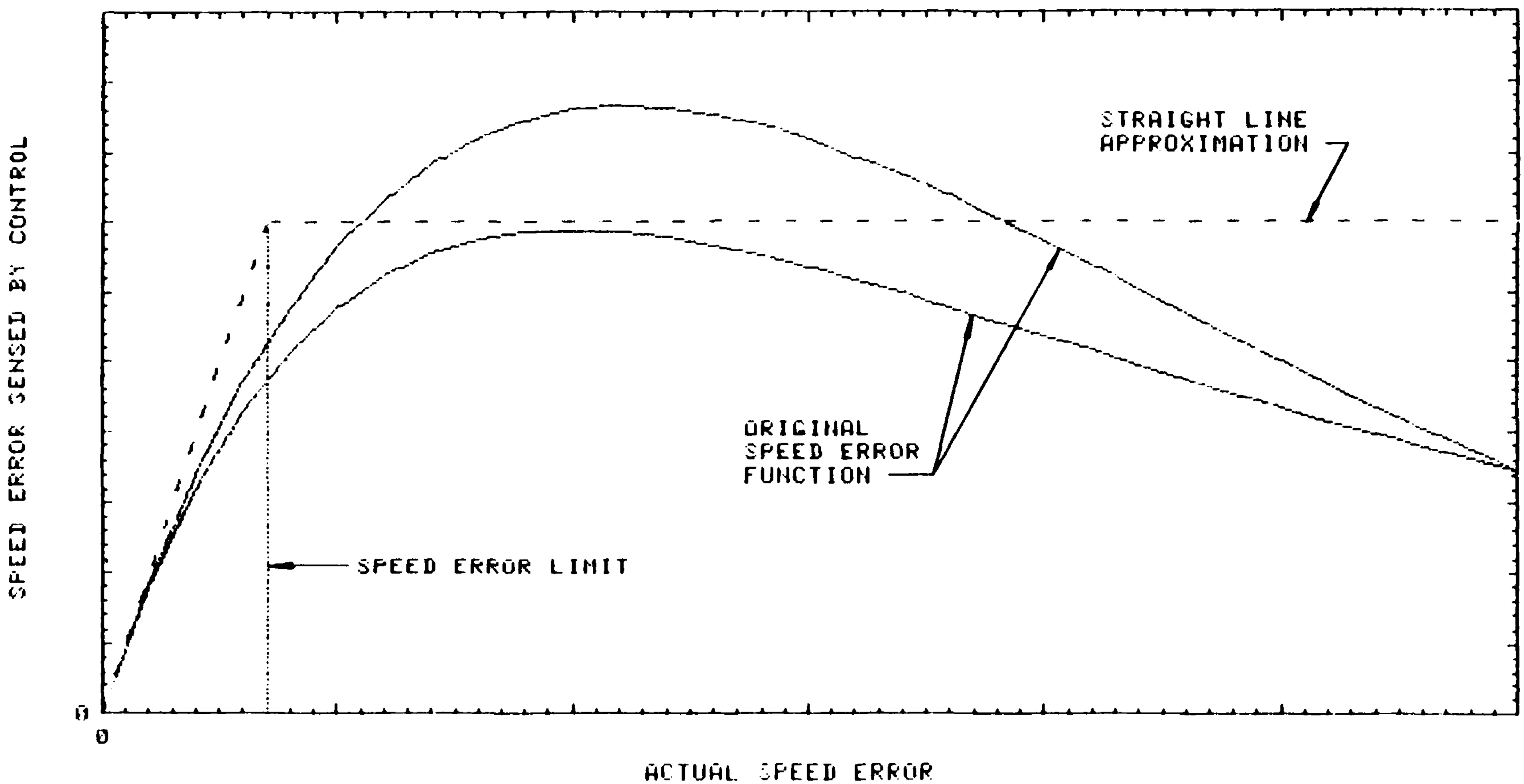
2. The input change rate limiter, as it will now be called, is altitude compensated.

The revised system is shown schematically in Figure 25. Now the input signal has a time delay which can be matched with the responsiveness of the engine. By doing this, the speed error is still kept small, but only because the engine is capable of following the input signal and not because of artificial means. In this manner, continuous closed-loop operation will result with the advantage of being able to compensate for system disturbances. And by altitude compensating the input rate limiter, the control will be properly adjusted for the decreased responsiveness of the engine at high altitudes.

With the proposed method of altitude compensation, P1 is used rather than P3 so as to be insensitive to variables other than altitude. This means that the inherent surge protection provided by P3 biasing is sacrificed. In addition, the control is no longer statically altitude compensated. However, with isochronous control, fuel flow will automatically be decreased at high altitudes to maintain engine speed. Gain compensation with engine speed, normally provided by P3 biasing, is accomplished through a variable gain fuel valve. A variable gain fuel valve would be characterized by a valve opening of increasing width, such that the sensitivity of the valve to changes in position increases with absolute fuel level. In this way, instead of the control gain increasing with P3 through the use of a mechanical multiplier. The gain increases (or decreases) with absolute flow level. If the contour of the fuel valve is selected properly, the effect is approximately the same.

This revised control concept was modeled and system performance compared with the speed error control. Comparative transients appear in Figures 26 through 30. As can be seen from these time traces, the limited input system behaves dynamically almost the same as the limited error system, with two major differences. A large transient at high altitude occurs much slower with the revised system, but with no speed overshoot (Figure 30). Also, Figures 31 and 32 show the effects of a 10% loop gain increase on each of the two systems. As can be seen, the limited error system reacts with a faster response, which could cause overfueling of the engine. The revised system compensates for the gain increase and the response characteristics go unchanged. This is the advantage of operating closed-loop.

A thorough investigation of this revised control system was not within the scope of this study, but it is believed to offer the same simplicity and flexibility as the speed error control. From a hardware standpoint, although the method of utilizing the pressure input is different than the speed error control system, most of the hardware should be about the same. Consequently, the revised control system should possess cost and reliability characteristics similar to the speed error control. Because this revised system offers the same advantages as the speed error control, with respect to simplicity and flexibility, without creating conditions of open-loop operation with the disturbance sensitivity that accompanies such operation, it is recommended that the revised speed error control be studied in greater depth as a possible low cost, simplified backup fuel control.



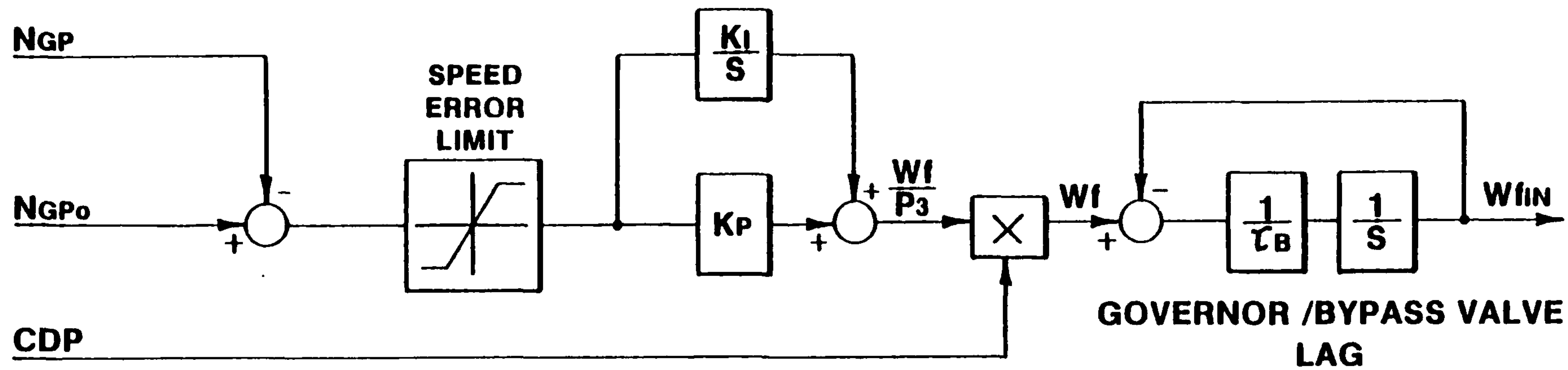
NAVAIR Speed Error Control Gain Function

Figure 1

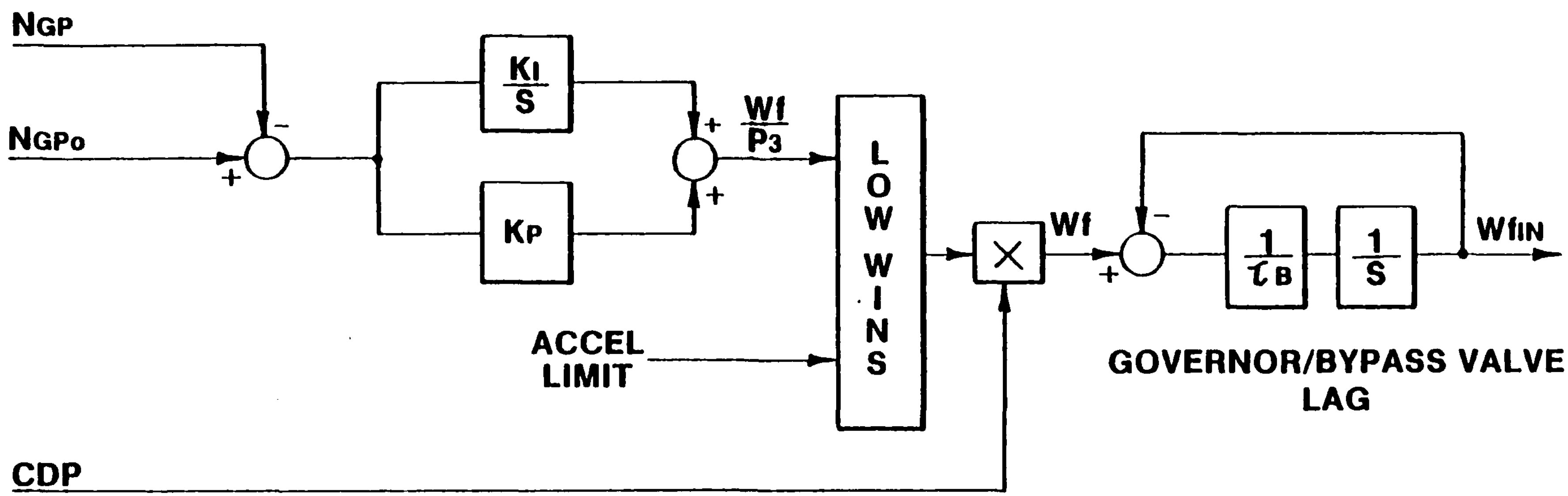
SUMMARY - DERIVATION OF FUNCTIONAL SPECIFICATION FOR FEASIBILITY STUDY

FUNCTION	ENGINE A	ENGINE B	ENGINE C	DESIGN SPECIFICATION
START	N_G DOT with Temp. Limiting	N_G DOT with Temp. Limiting	N_G DOT with Temp. and Wf DOT Limiting	Speed Error
ACCELERATION	N_GDOT with Temp. Limiting	N_GDOT with Temp. Limiting	N_GDOT with Temp. and Wf DOT Limiting	Speed Error
DECELERATION	N_GDOT = Constant	$Wf/P_3 = f(N_G, VG)$	N_GDOT with Temp. and Wf DOT Limiting	Speed Error
GAS PRODUCER GOVERNOR (GPG)	Not Specified	Proportional	Isochronous	Isochronous
POWER TURBINE GOVERNOR (PTG)	Not Specified	Isochronous	Isochronous	Not Required
LOAD COMPENSATION (Collective Pitch, CP)	Not Specified)	CP Resets PTG	CP Resets PTG	Not Required
HELICOPTER ROTOR DYNAMIC COMPENSATION	Not Specified	Second Order Notch Filter	Not Specified	Not Required
LOAD SHARING	Reset PTG of Low Engine to Match Torque Signals	Reset PTG of Low Engine to Match Torque Signals	Reset PTG of Low Engine to Match Torque Signals	Not Required
TEMPERATURE LIMITING	Not Specified	Not Specified	T_{4B} Resets GPG	Not Required
VARIABLE GEOMETRY (V_G):			$V_G = f(N_G/\sqrt{\theta})$	
STATOR VANES (VSV)	No	$VSV = f(N_G/\sqrt{\theta})$		$V_G = f(N_G, T_1)$
BLEED VALVES (VBV)	$VBV = f(N_G/\sqrt{\theta})$	Not Specified		
POWER TURBINE OVERSPEED PROTECTION	Resets Fuel Flow	Resets Fuel Flow	Shuts off Fuel Flow	Not Required
GAS PRODUCER OVERSPEED PROTECTION	Through Primary GPG	Through Primary GPG	Shuts off Fuel Flow	Through Primary GPG

Figure 2

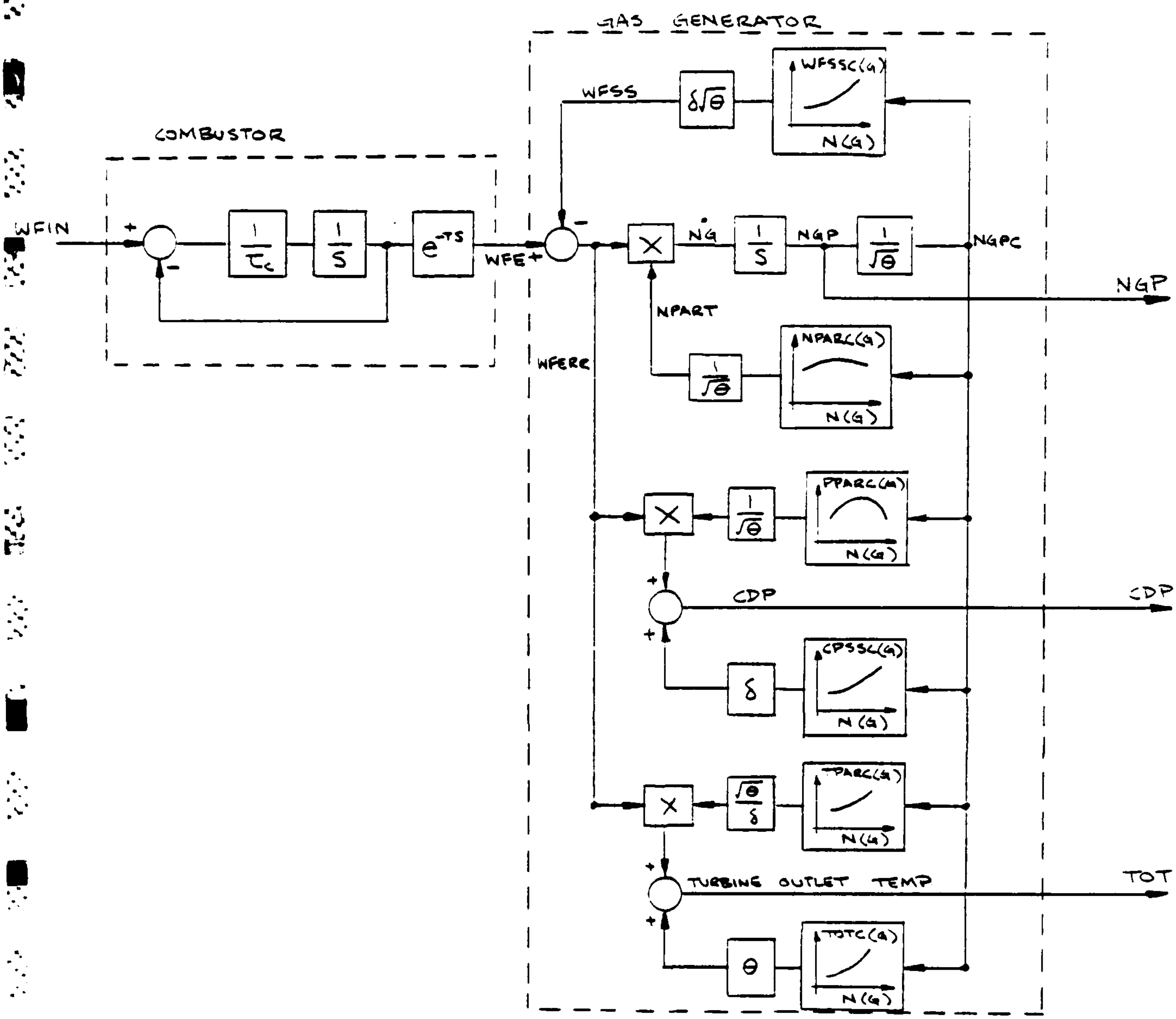


SIMPLIFIED FUEL CONTROL MODEL



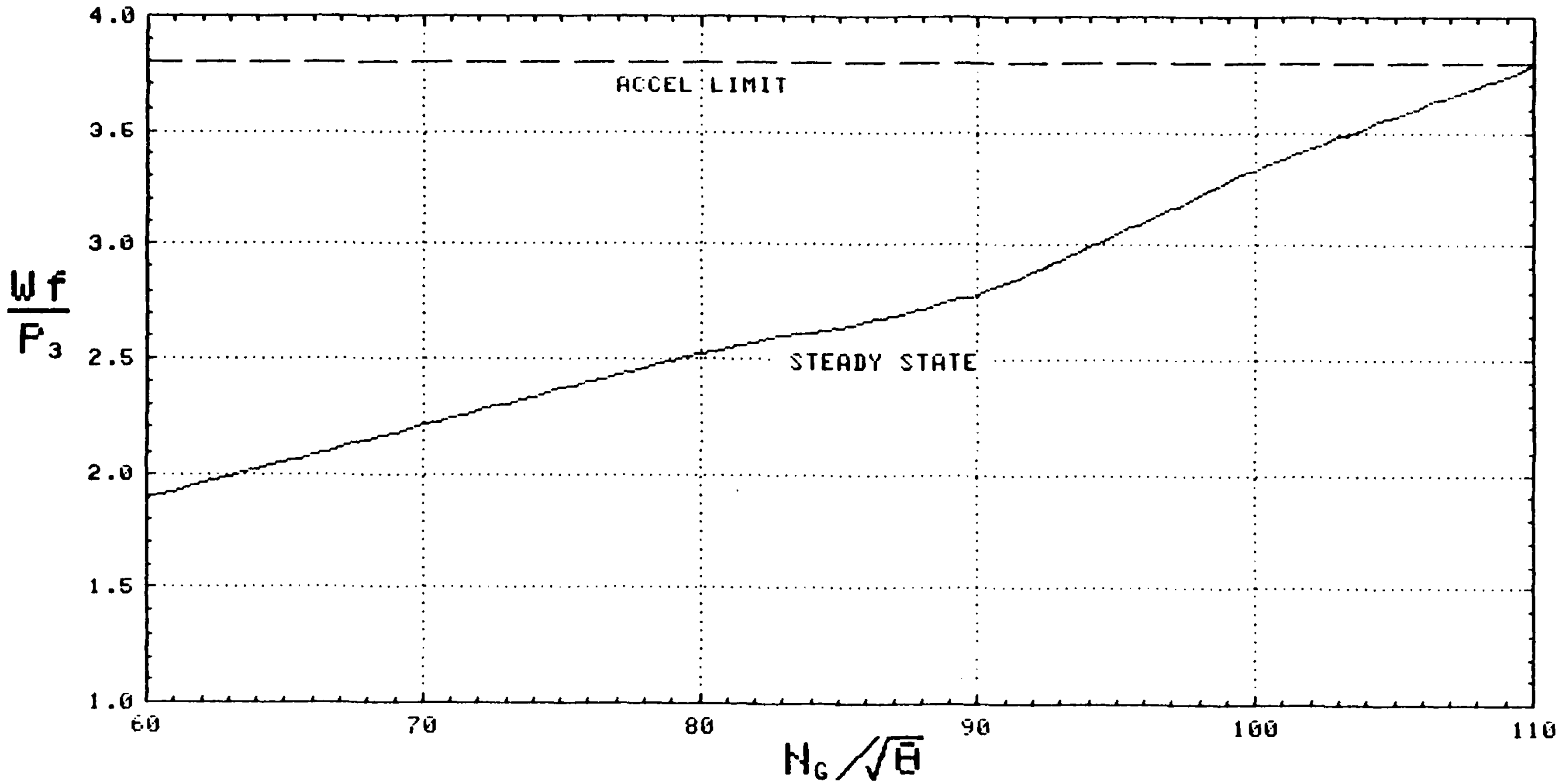
BASELINE CONTROL MODEL

Figure 3



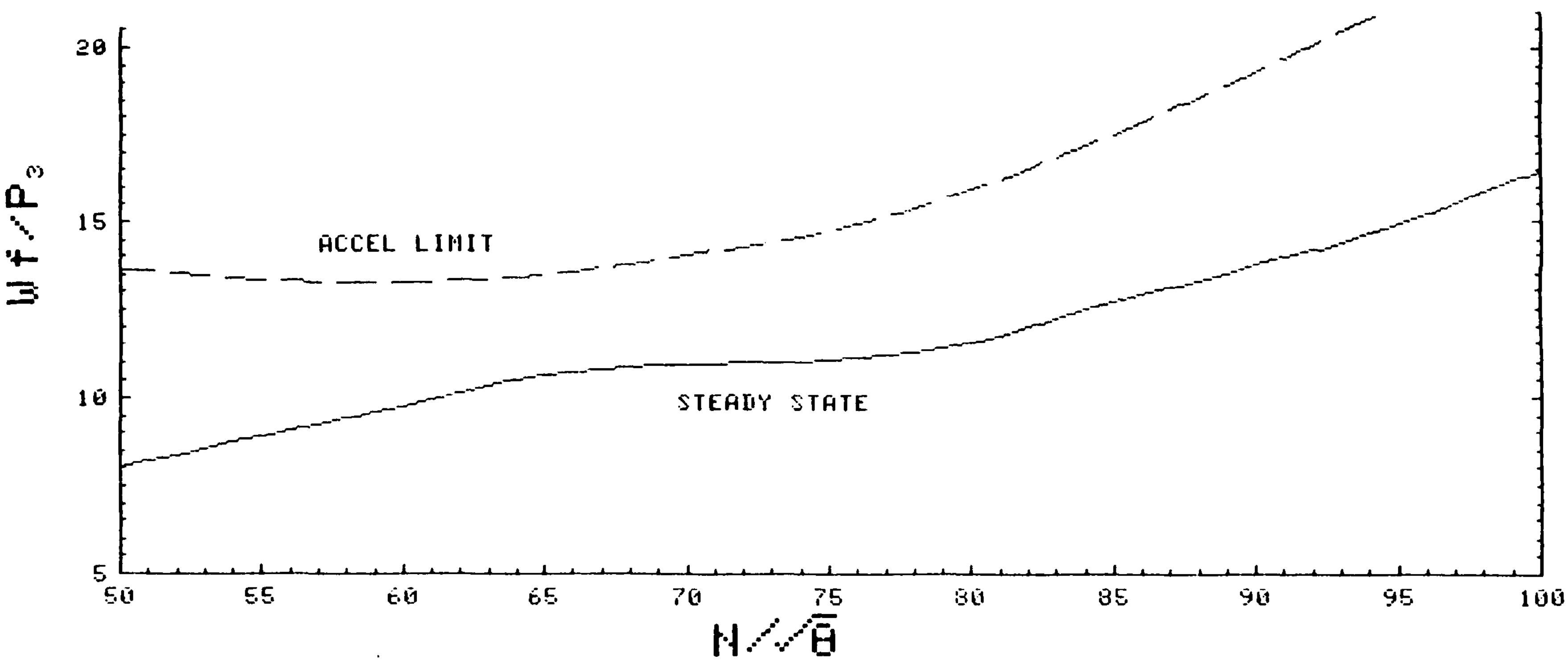
Engine Core Model Used in Simulations

Figure 4



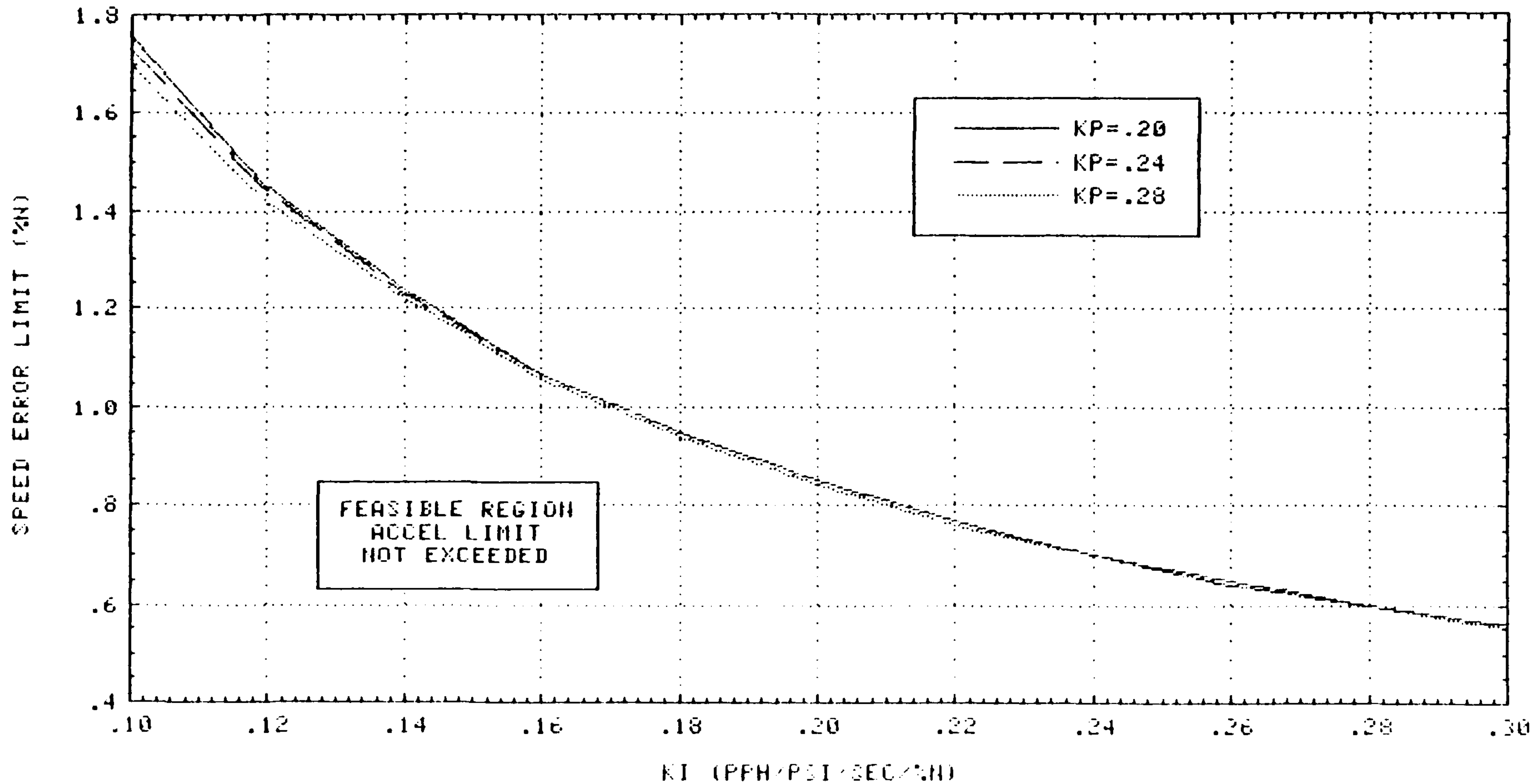
Engine Characteristics - 600 SHP Engine

Figure 5



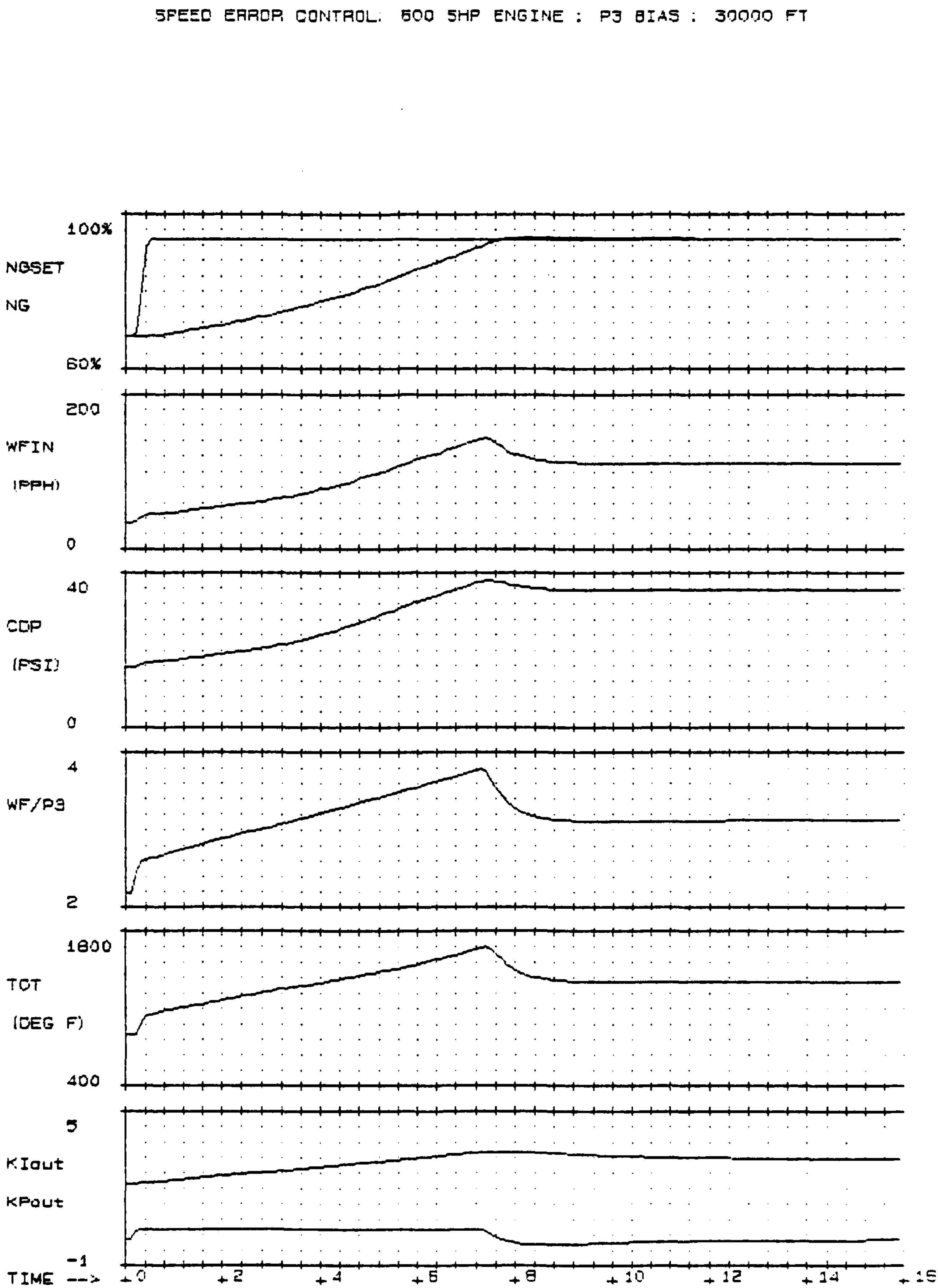
Engine Characteristics - 5000 SHP Engine

Figure 6



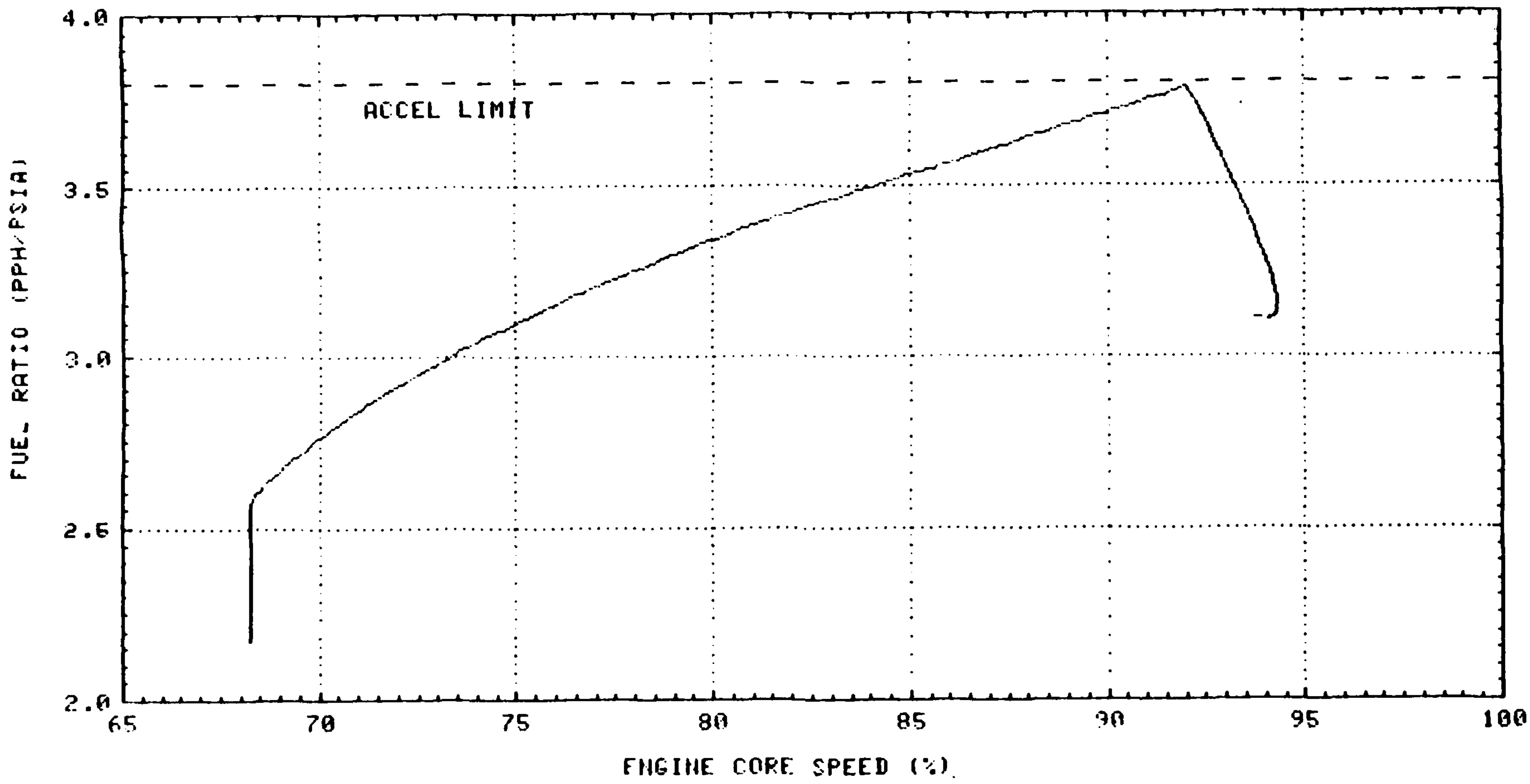
Control Gain/Speed Error Limit Relationship
600 SHP Engine

Figure 7



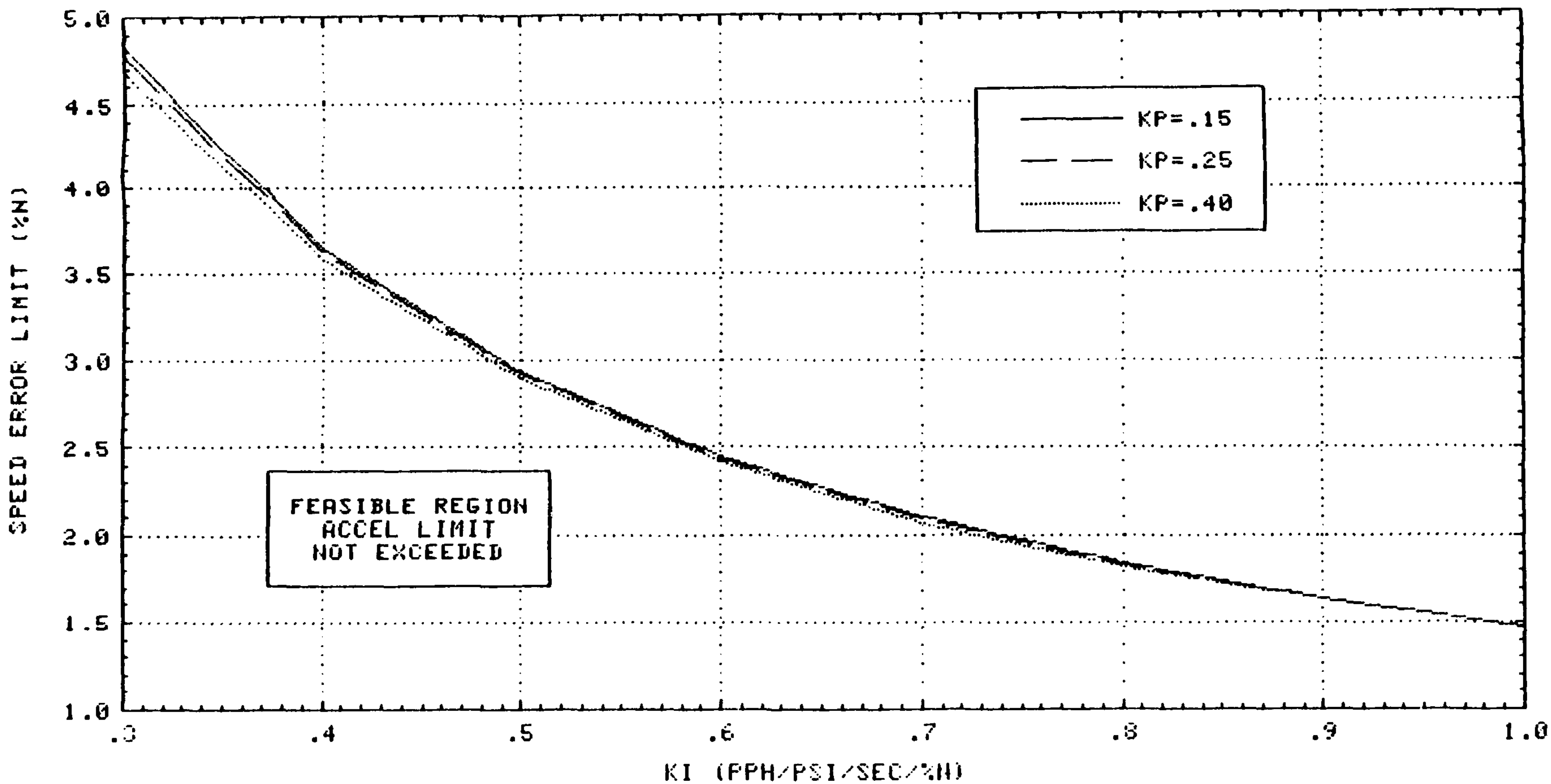
SPEED ERROR CONTROL. 600 SHP ENGINE : P3 BIAS : 30000 FT
100%
NGSET
NG
60%
200
WFIN
(PPH)
0
40
CDP
(PSI)
0
4
WF/P3
2
1800
TOT
(DEG F)
400
5
KIout
KPout
-1
TIME -->
0
2
4
6
8
10
12
14
16

Figure 8



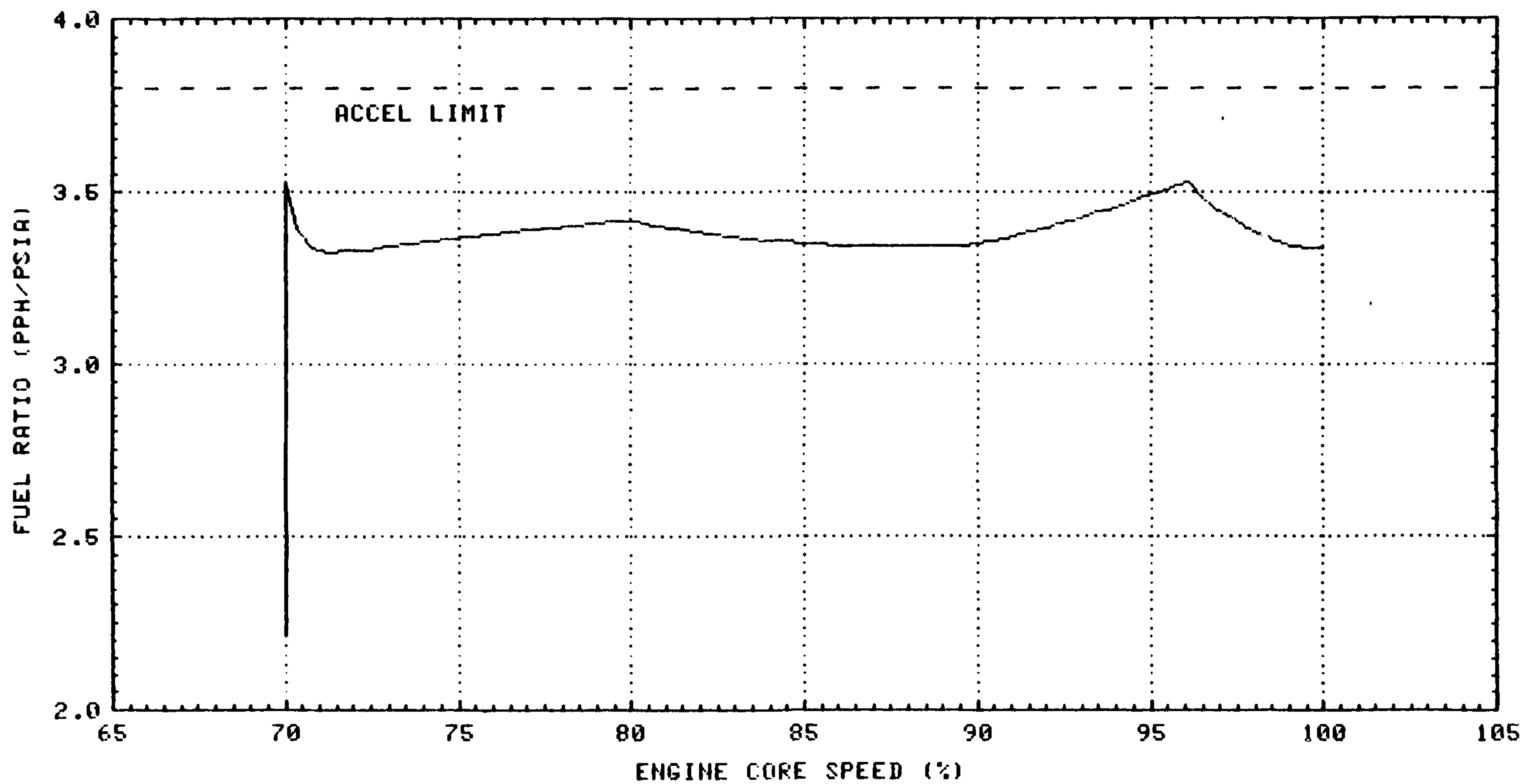
Speed Error Control Output vs Engine Speed
30% Speed Change - 30,000 Ft/-6°F
600 SHP Engine

Figure 9



Control Gain/Speed Error Limit Relationship - 5000 SHP Engine

Figure 10



Speed Error Control Transient Characteristics - Pl Biasing
30% Speed Change - S.L./Std Day
600 SHP Engine

Figure 11

SPEED ERROR CONTROL: 5000 SHP ENGINE : P3 BIAS , SEA LEVEL

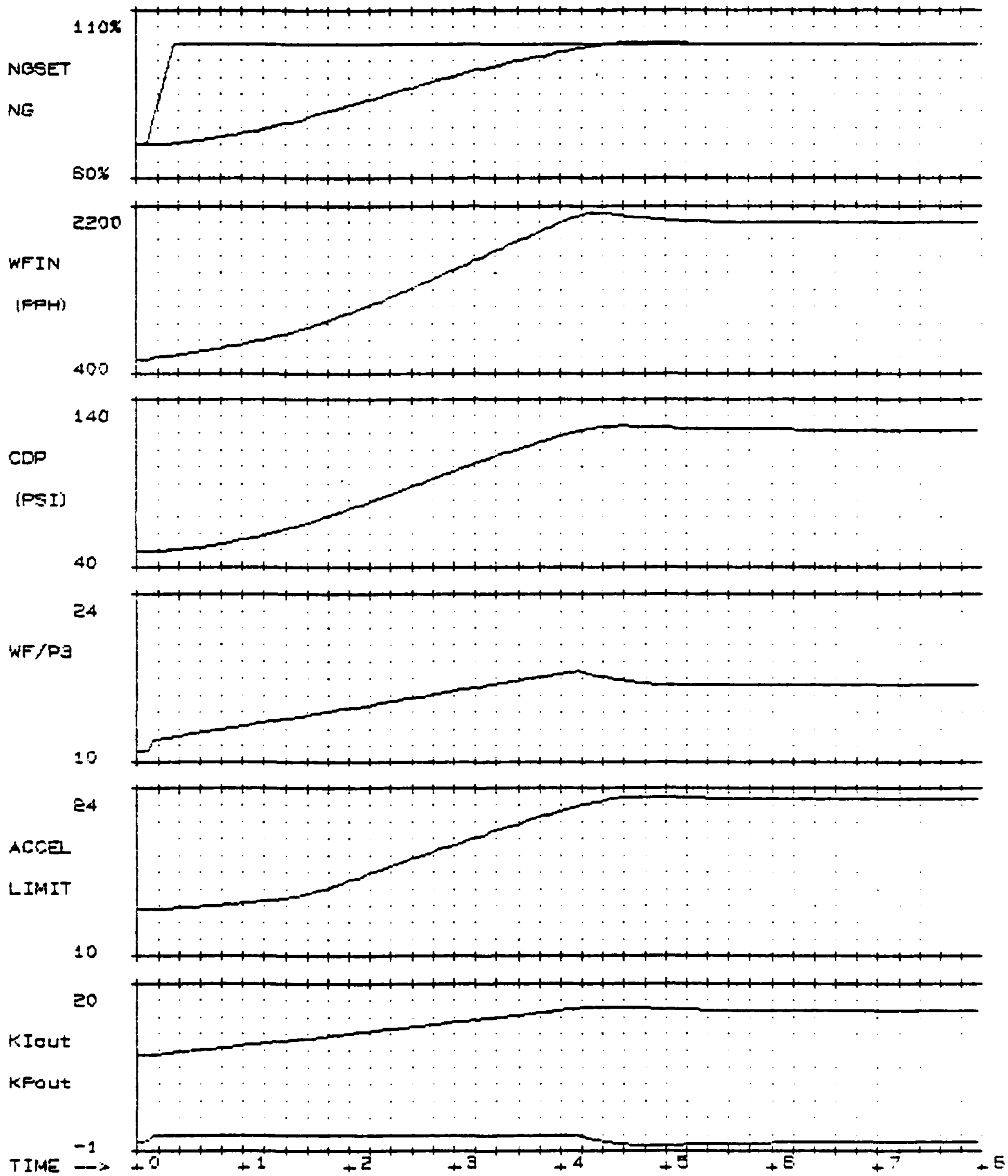
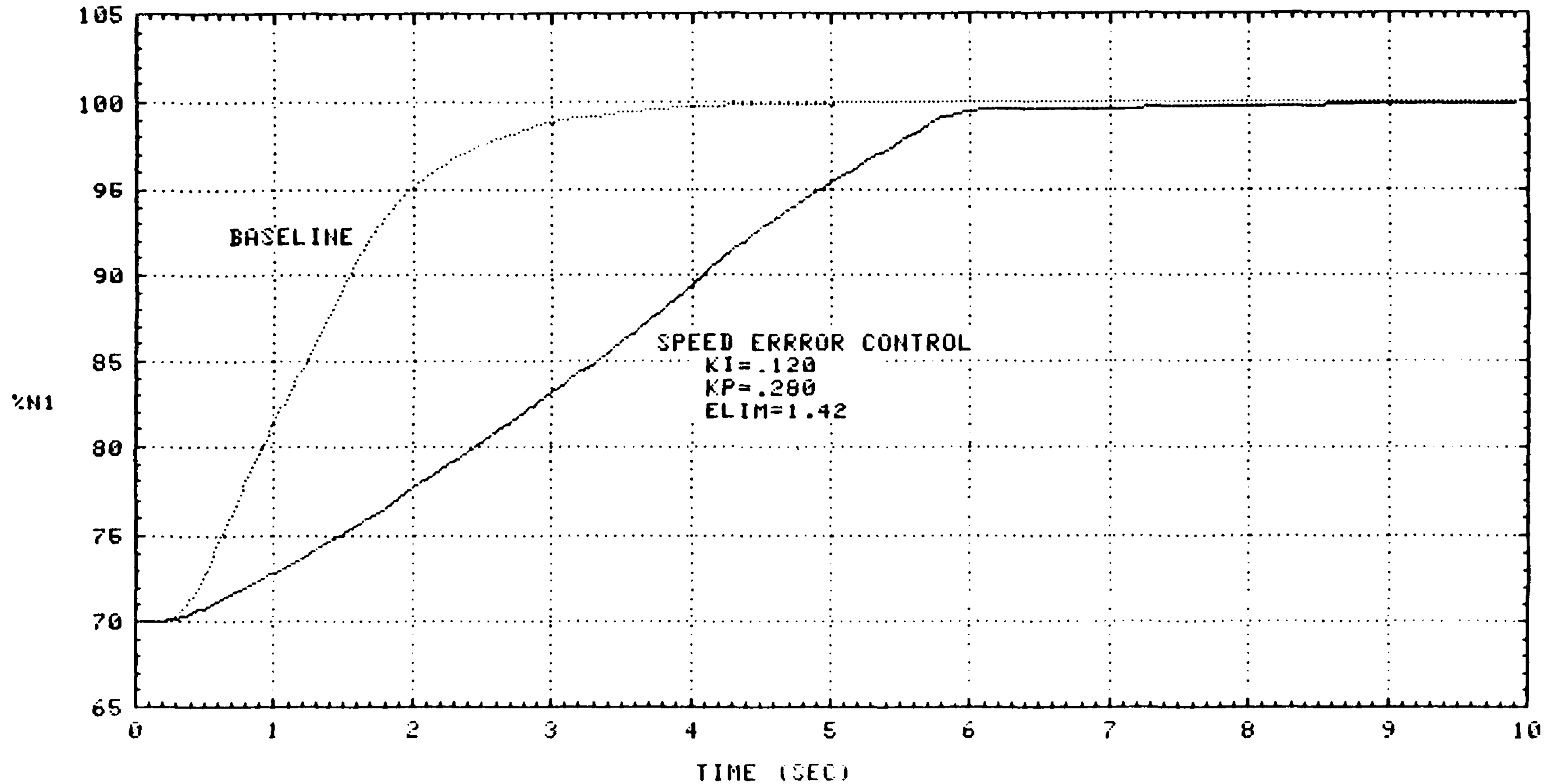
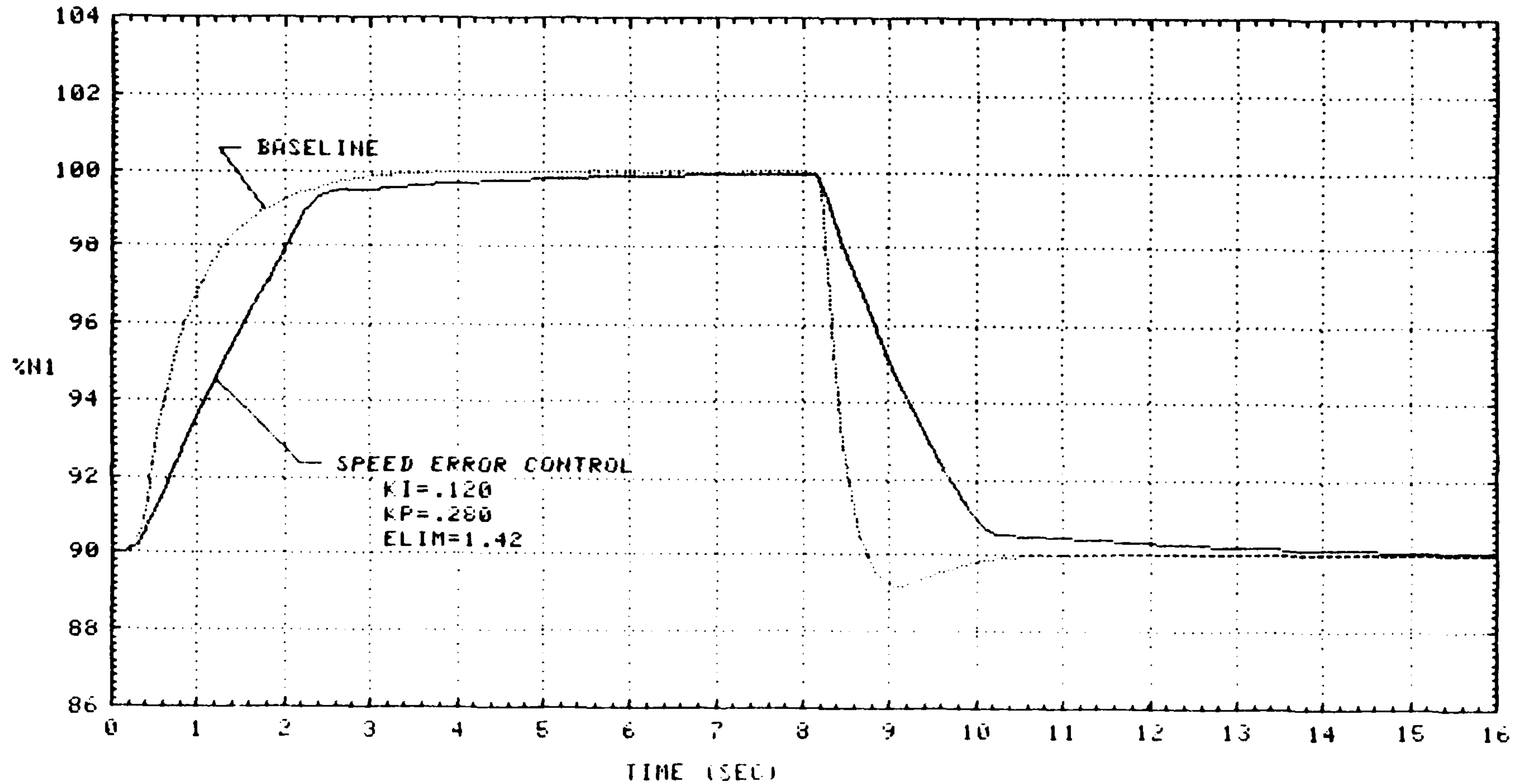


Figure 12



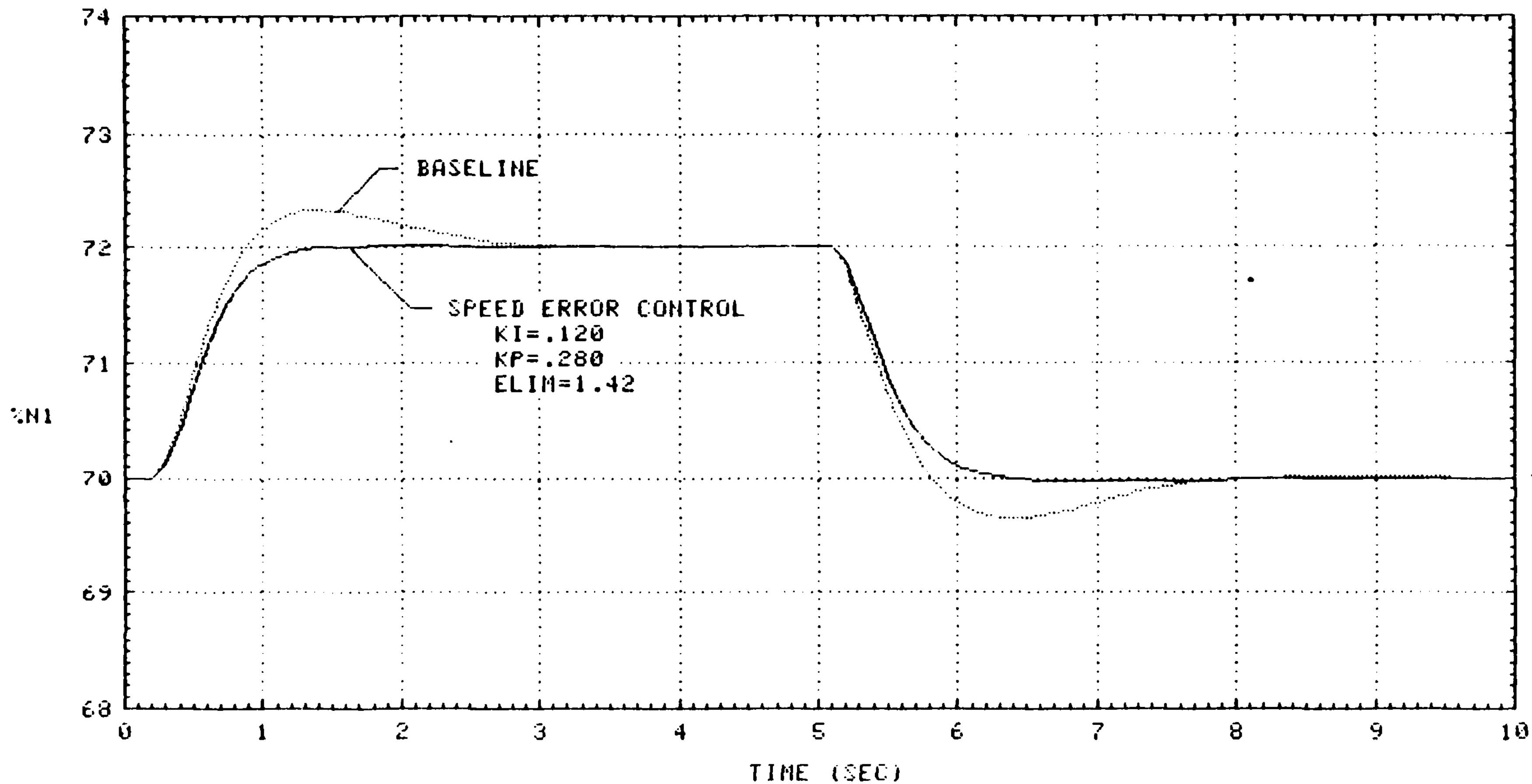
Speed Error Control Performance Comparison
30% Speed Change - S.L./Std Day
600 SHP Engine

Figure 13



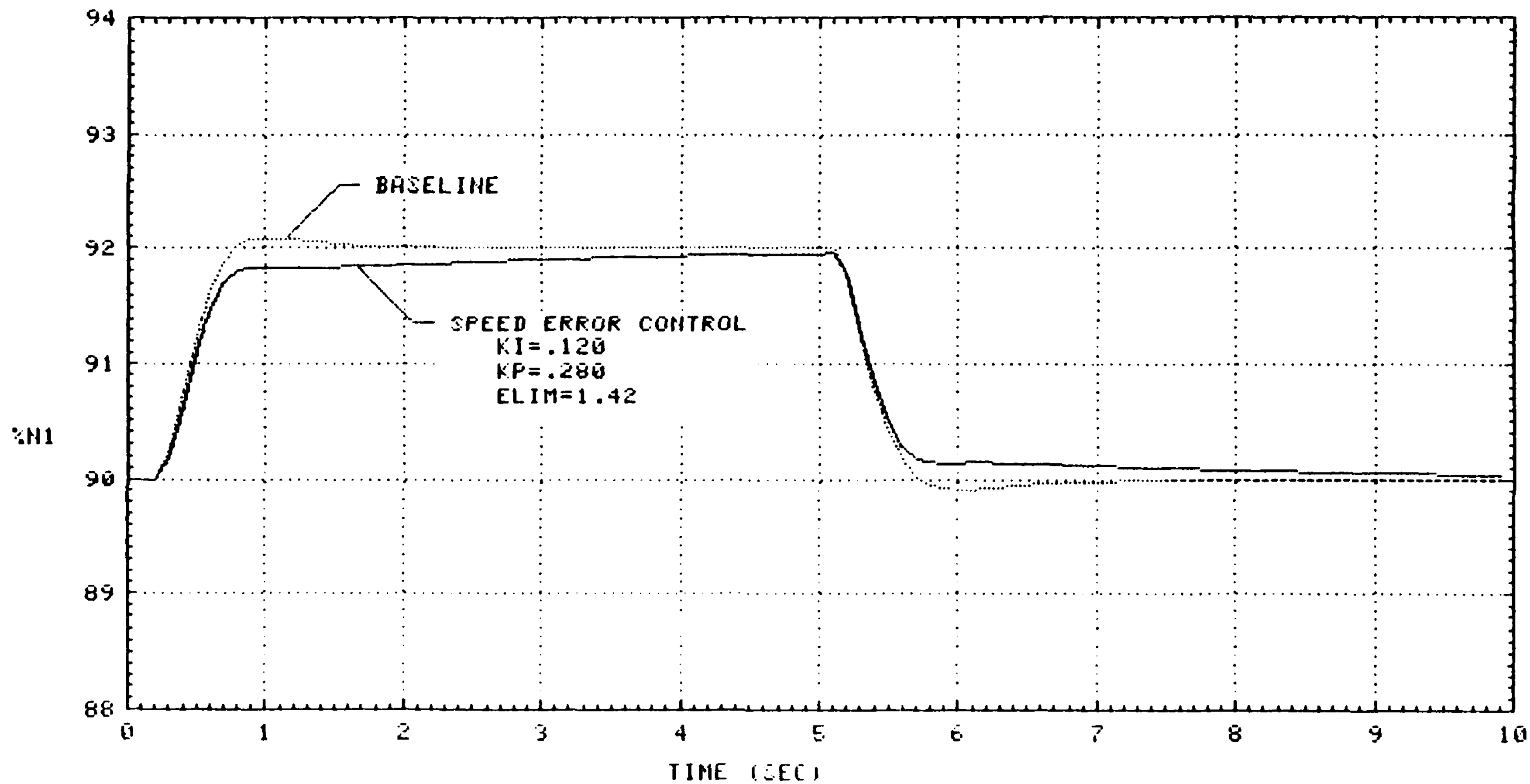
Speed Error Control Performance Comparison
10% Speed Change - S.L./Std Day
600 SHP Engine

Figure 14



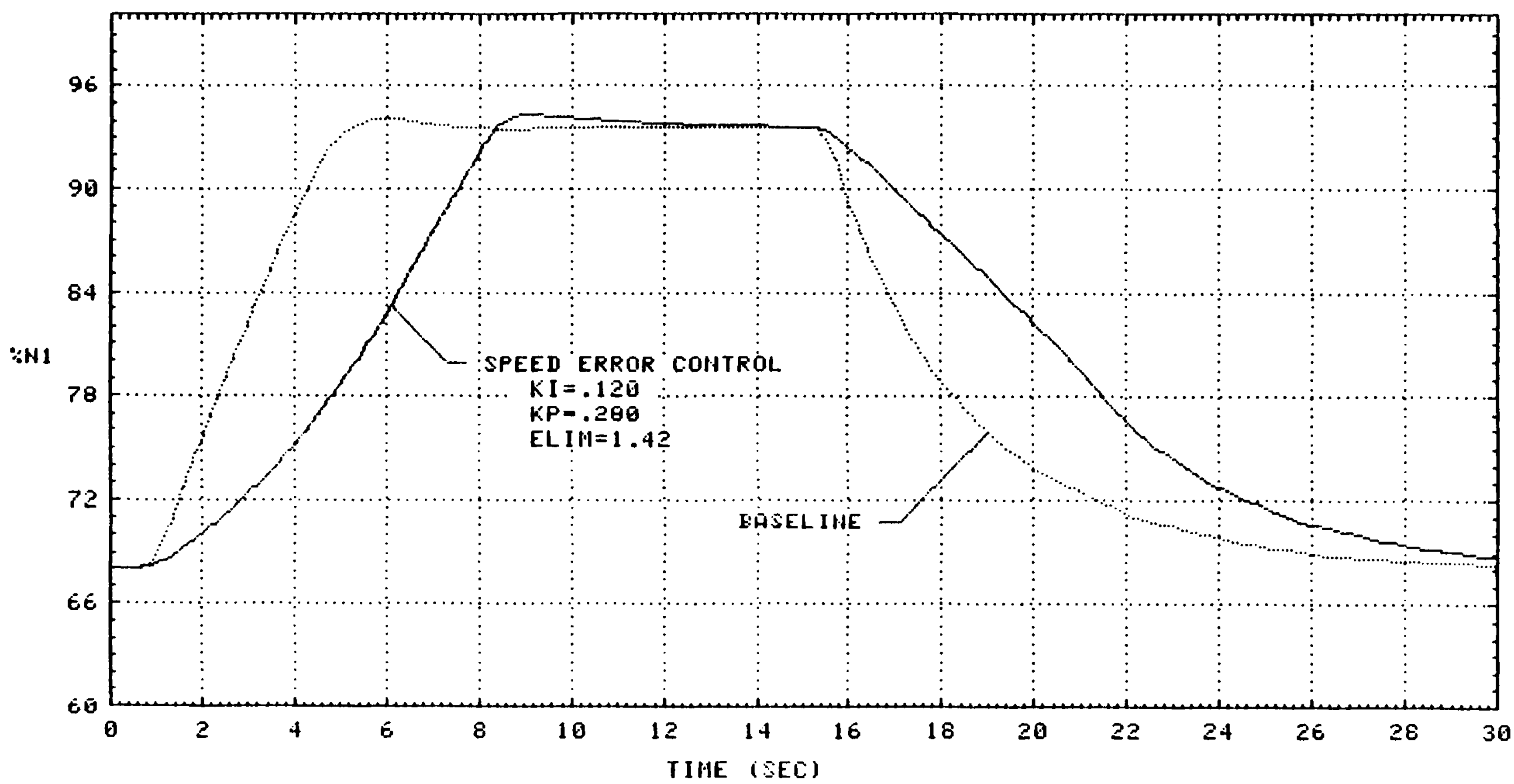
Speed Error Control Performance Comparison
2% Speed Change - S.L./Std Day
600 SHP Engine

Figure 15



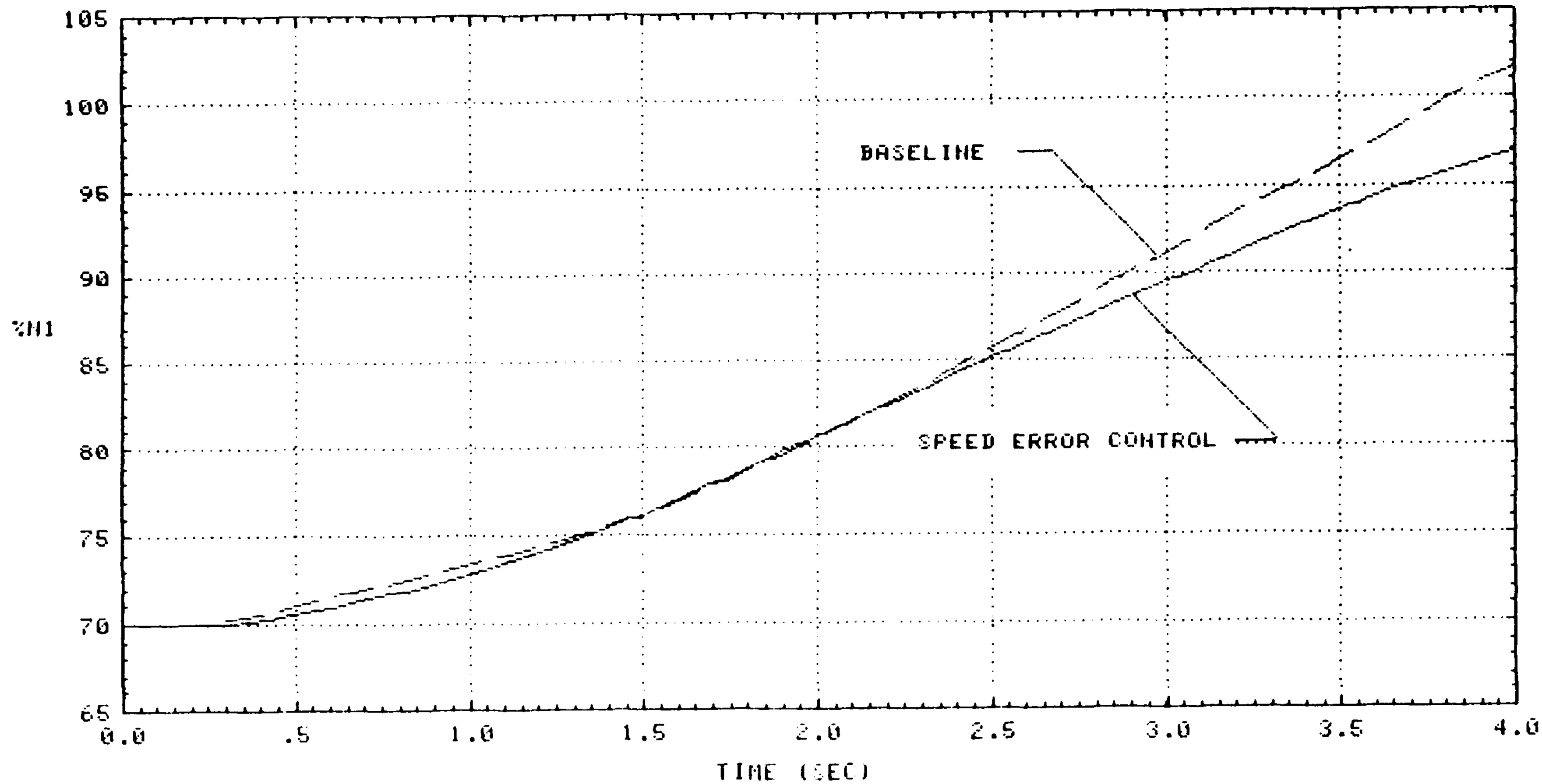
Speed Error Control Performance Comparison
2% Speed Change - S.L./Std Day
600 SHP Engine

Figure 16



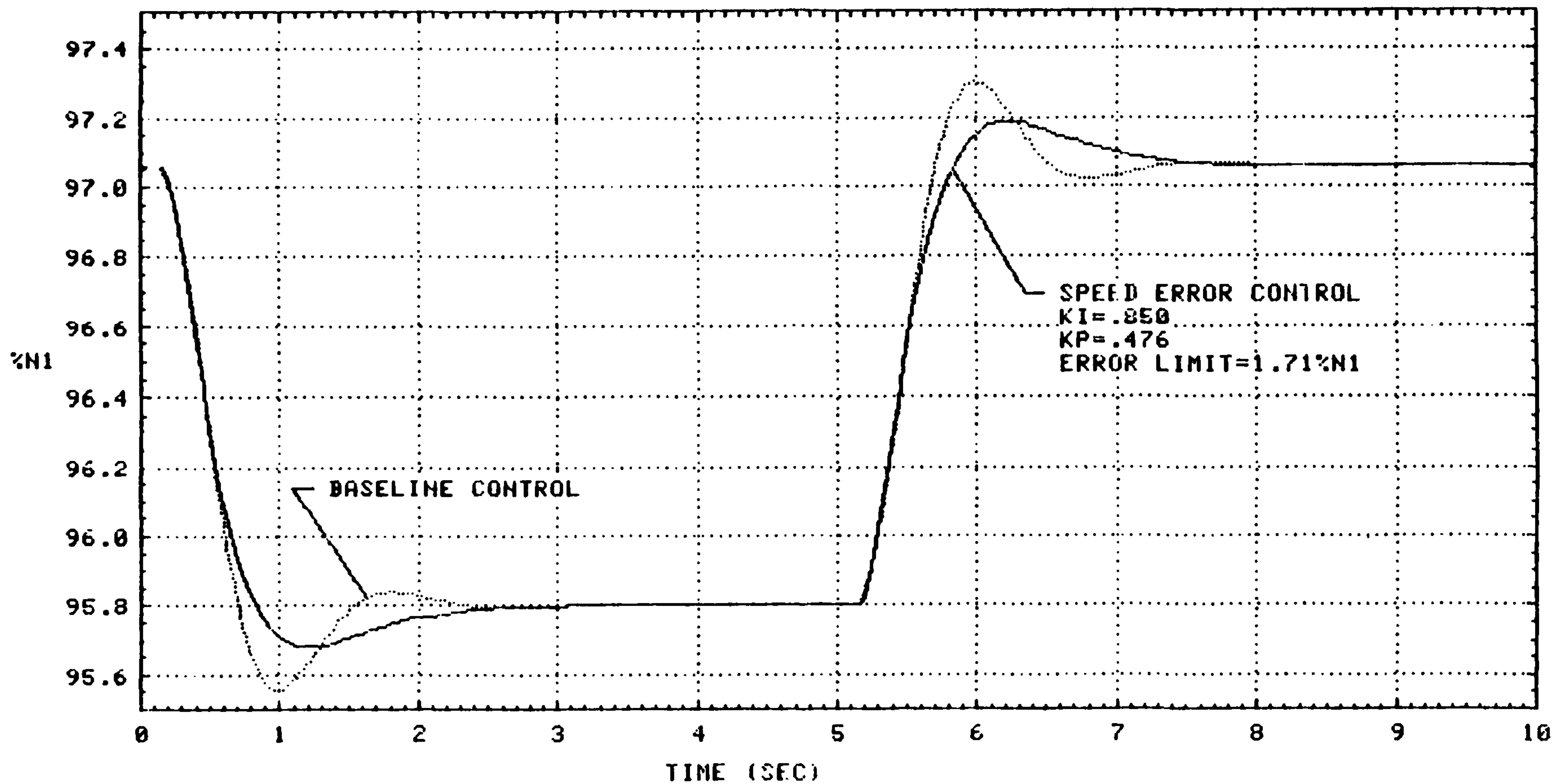
Speed Error Control Performance Comparison
30% Speed Change - 30,000 Ft/-6°F
600 SHP Engine

Figure 17



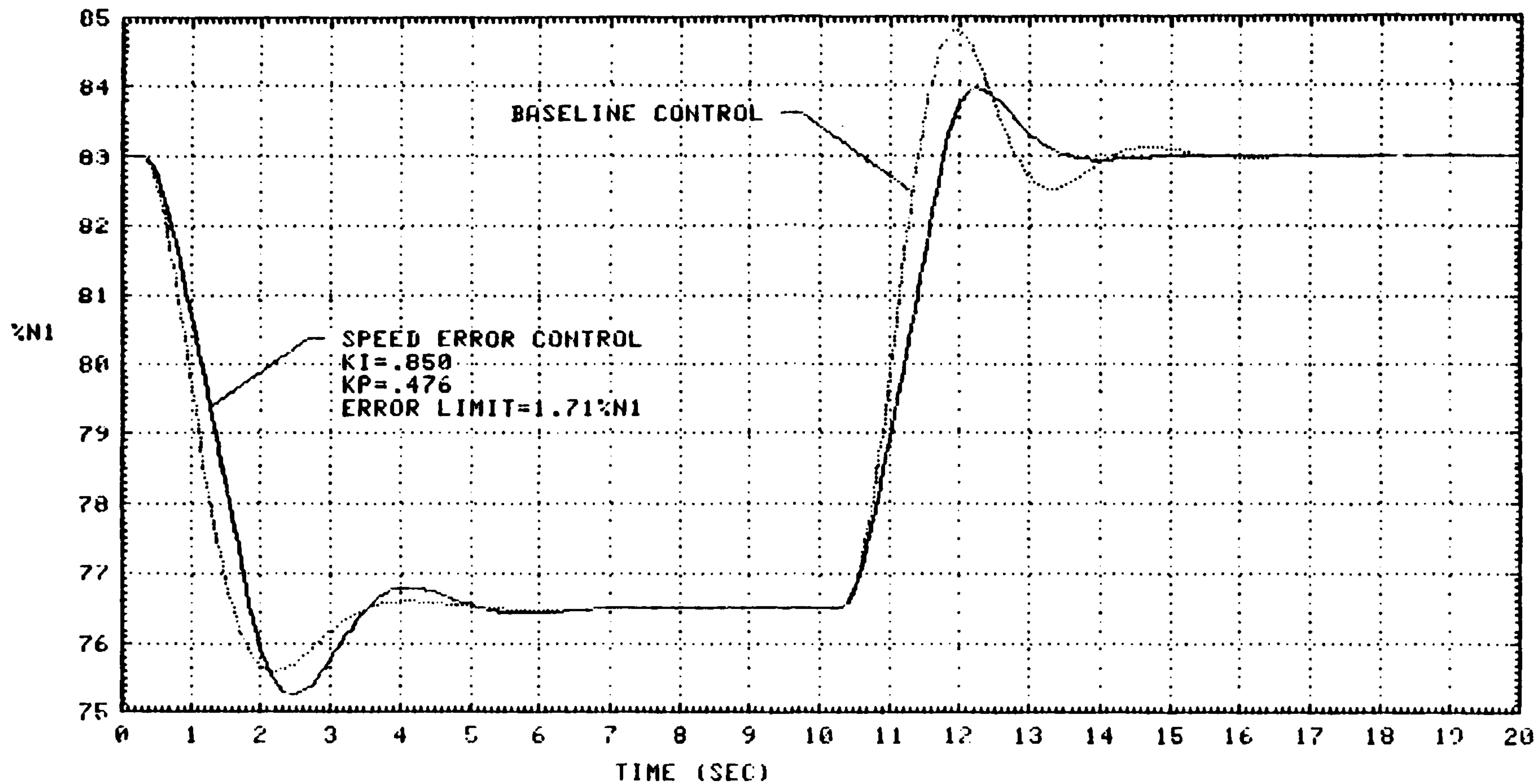
Speed Error Control Performance Comparison
30% Speed Change - S.L./Std Day
5000 SHP Engine

Figure 18



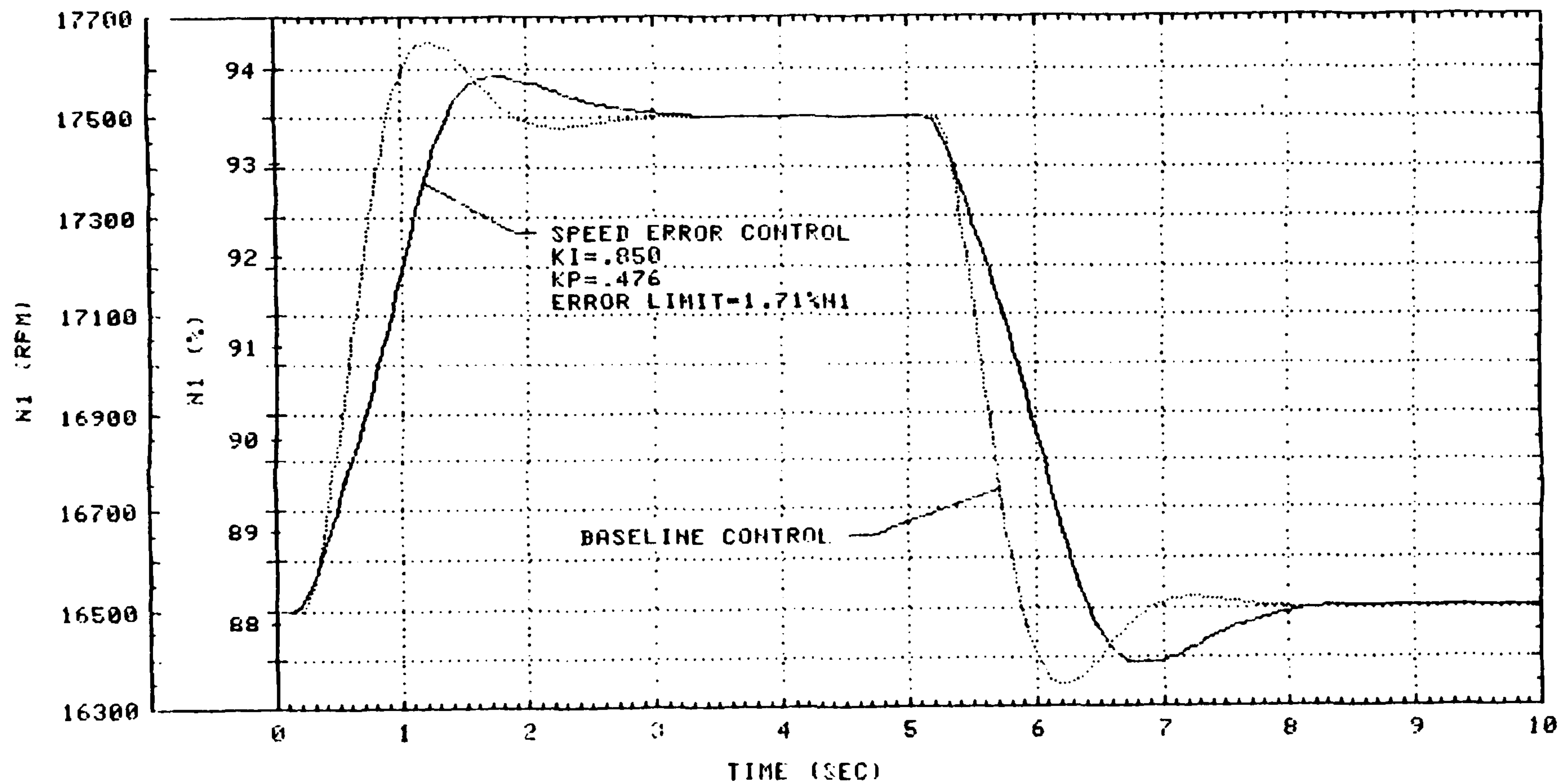
Speed Error Control Performance Comparison
1.3% Speed Change - S.L./Std Day
5000 SHP Engine

Figure 19



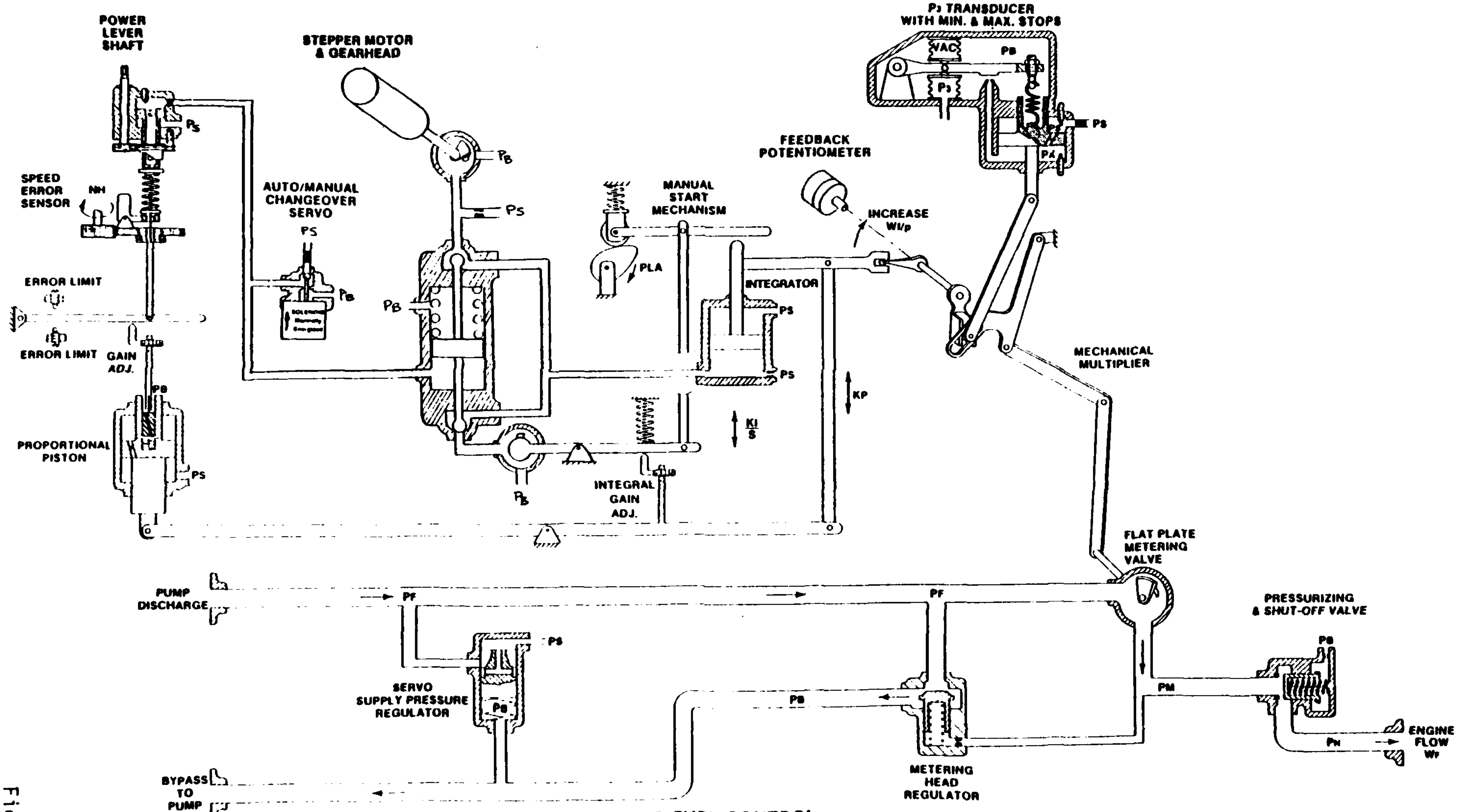
Speed Error Control Performance Comparison
6.5% Speed Change - S.L./Std Day
5000 SHP Engine

Figure 20



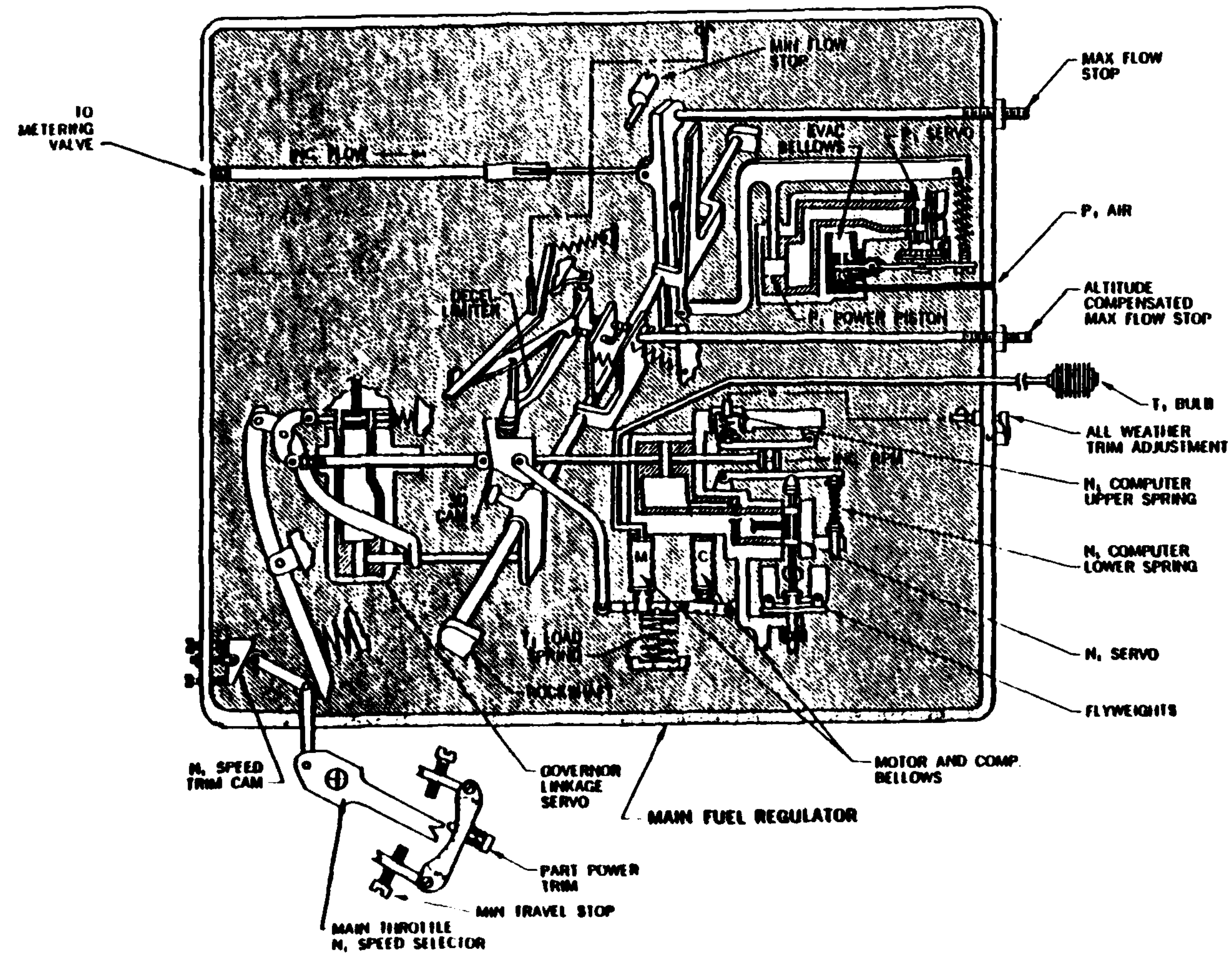
Speed Error Control Performance Comparison
5.3% Speed Change - S.L./Std Day
5000 SHP Engine

Figure 21



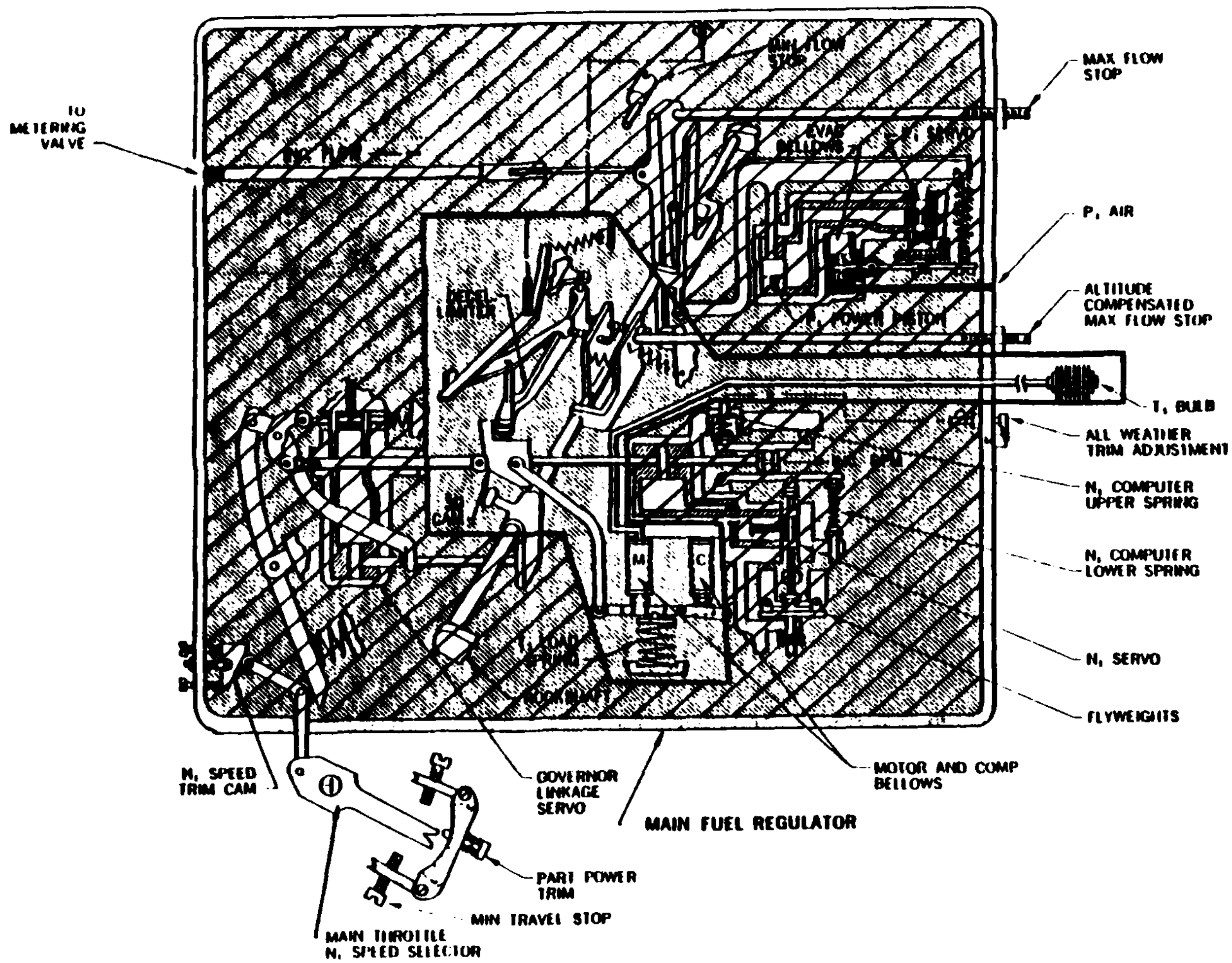
NAPC SIMPLIFIED FUEL CONTROL MECHANICAL MULTIPLIER SYSTEM WITH FADEC INTERFACES

Figure 22



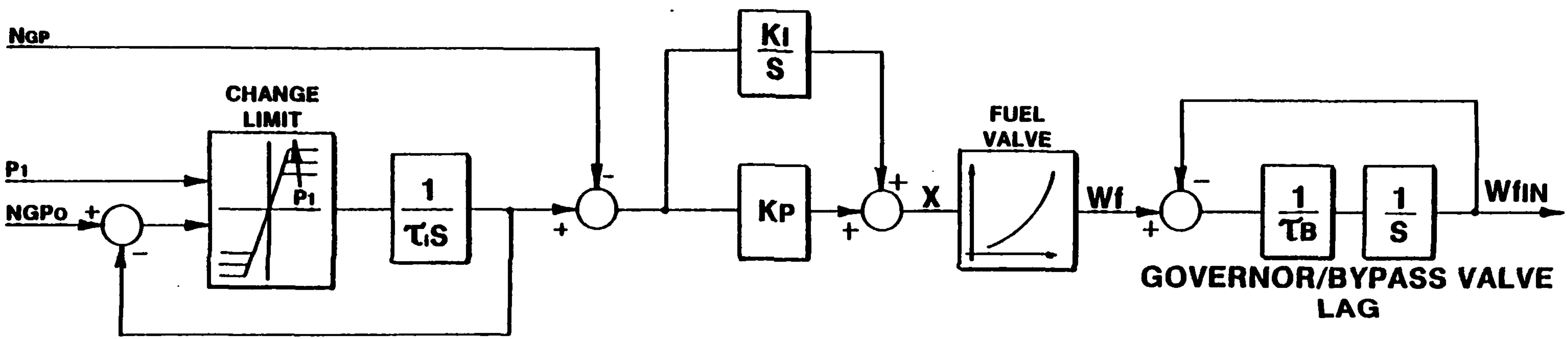
Baseline Hydromechanical Control

Figure 23



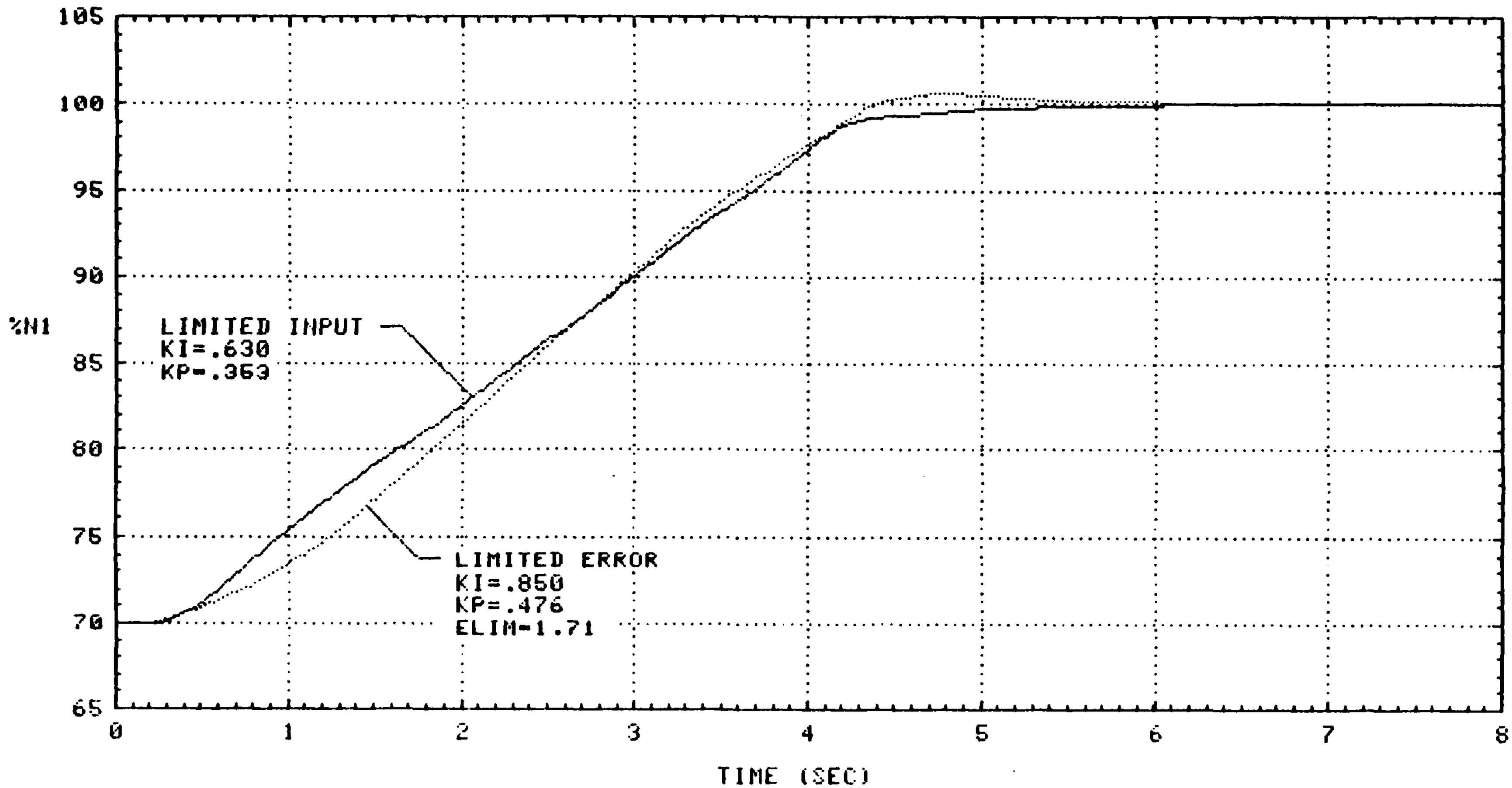
BASELINE CONTROL HARDWARE ELIMINATED (NOT SHADED)
BY SPEED ERROR CONTROL

Figure 24



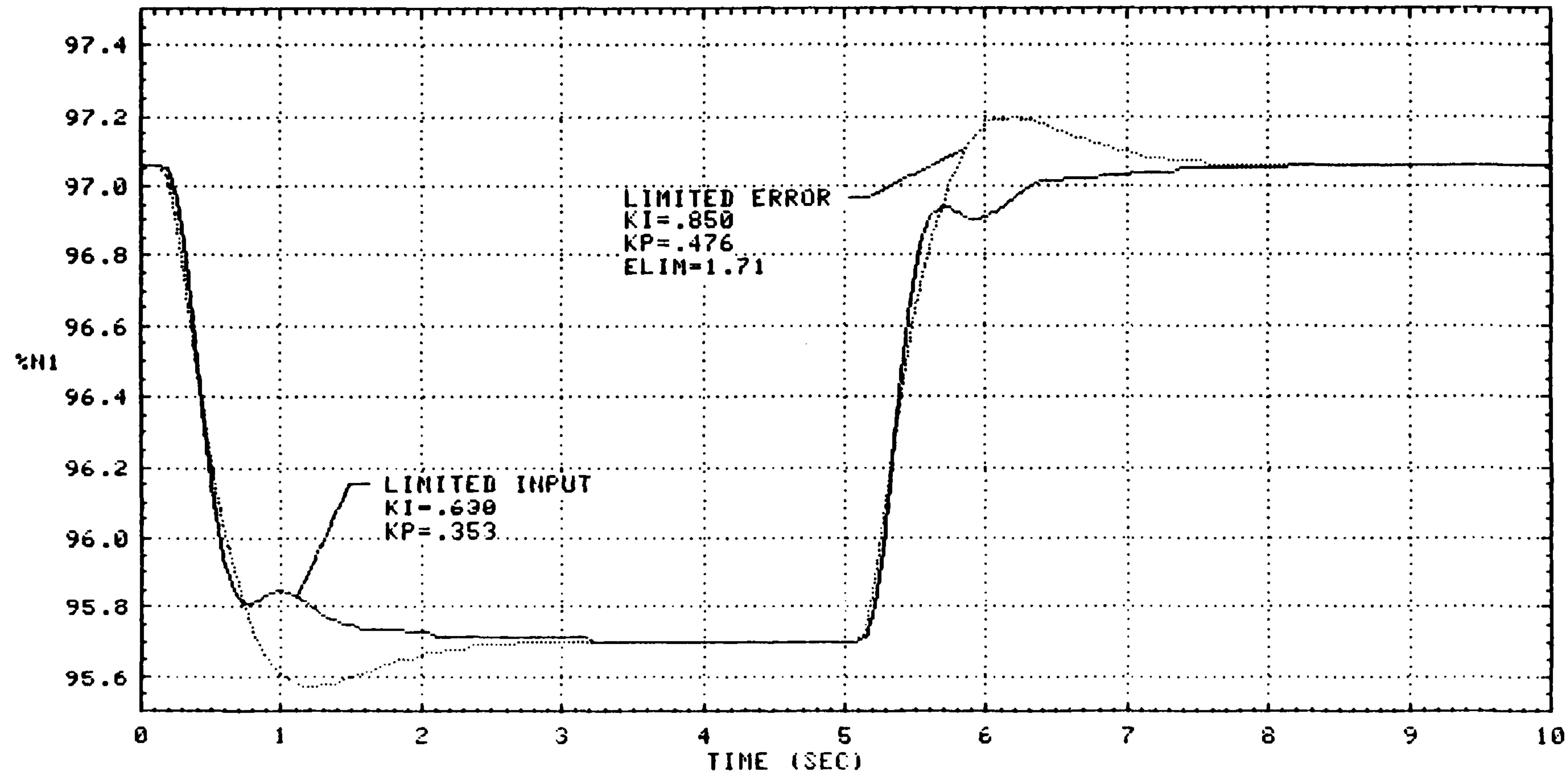
SIMPLIFIED FUEL CONTROL MODEL
LIMITED INPUT SYSTEM

Figure 25



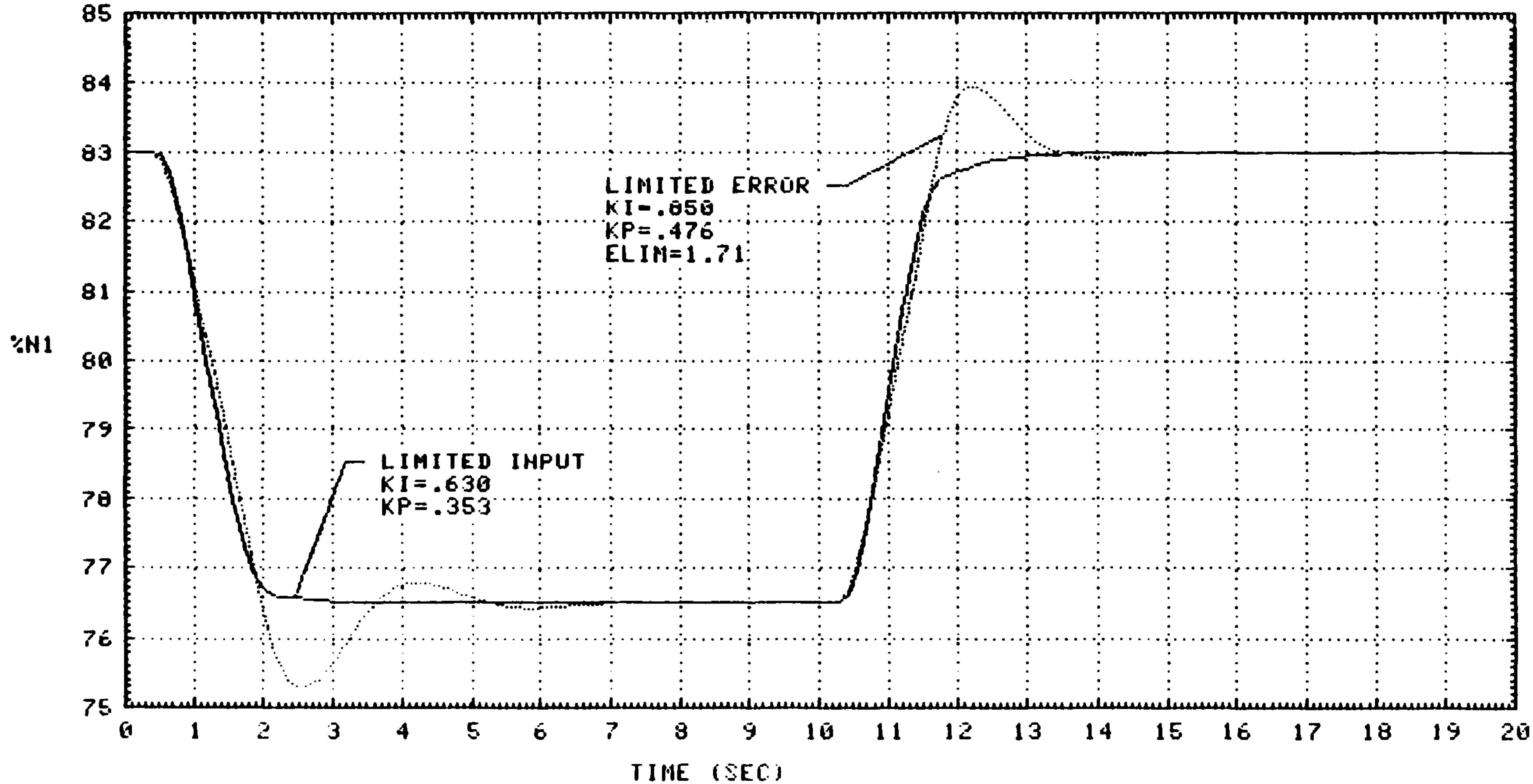
Revised Control Performance
S.L./Std Day
5000 SHP Engine

Figure 26



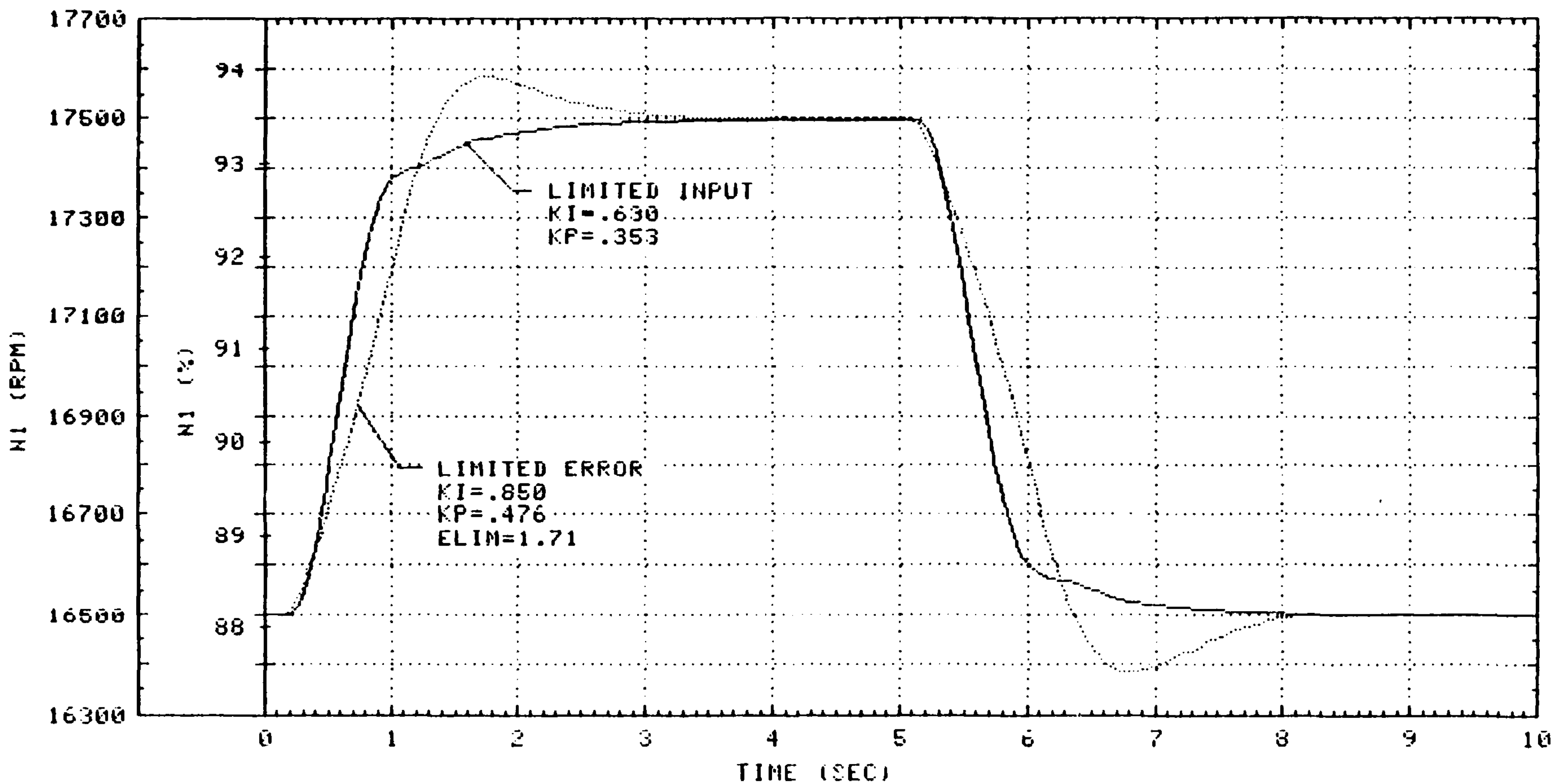
Revised Control Performance
S.L./Std Day
5000 SHP Engine

Figure 27



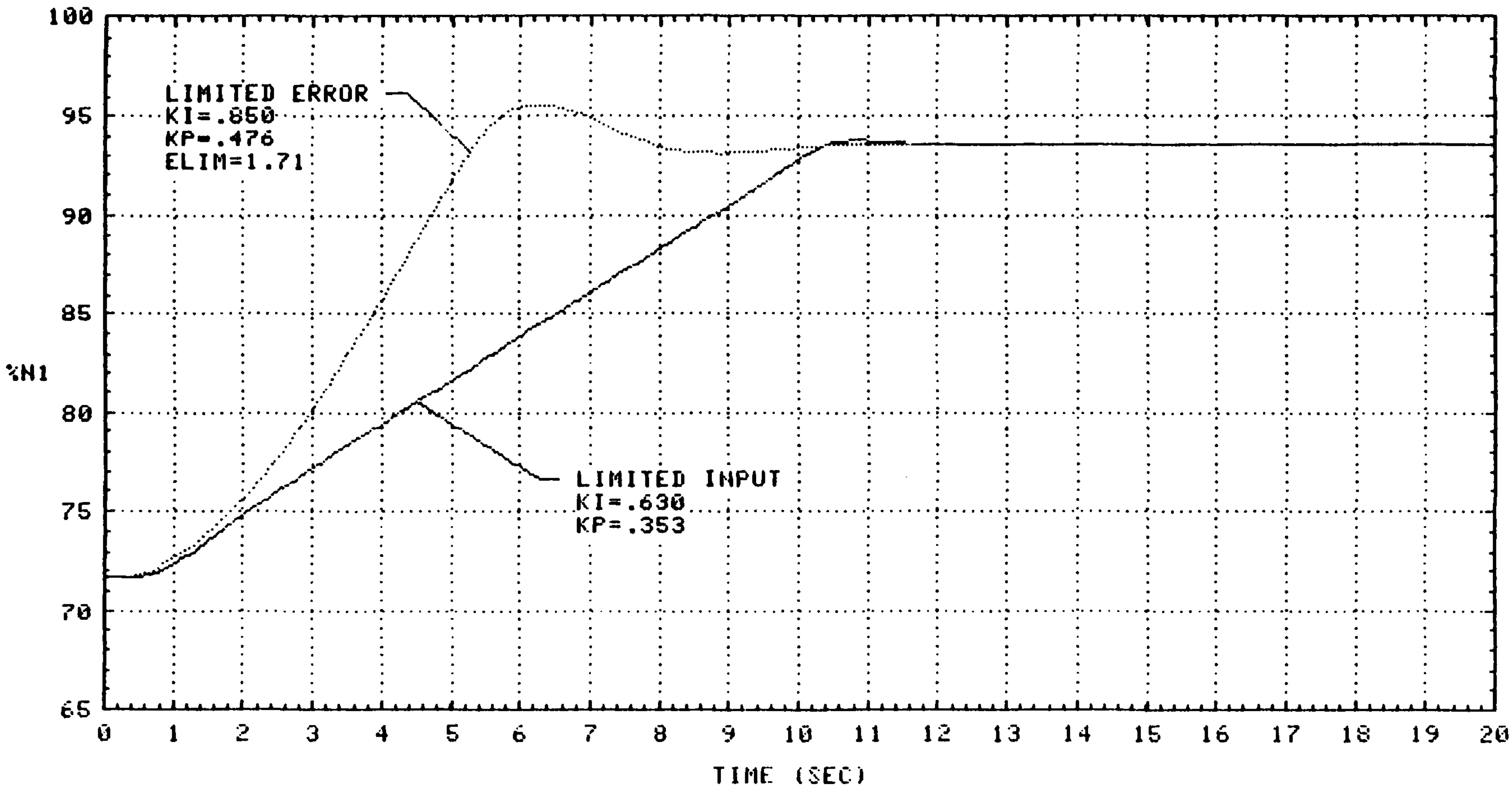
Revised Control Performance
S.L./Std Day
5000 SHP Engine

Figure 28



Revised Control Performance
S.L./Std Day
5000 SHP Engine

Figure 29



Revised Control Performance
30,000 Ft/-6°F
5000 SHP Engine

Figure 30

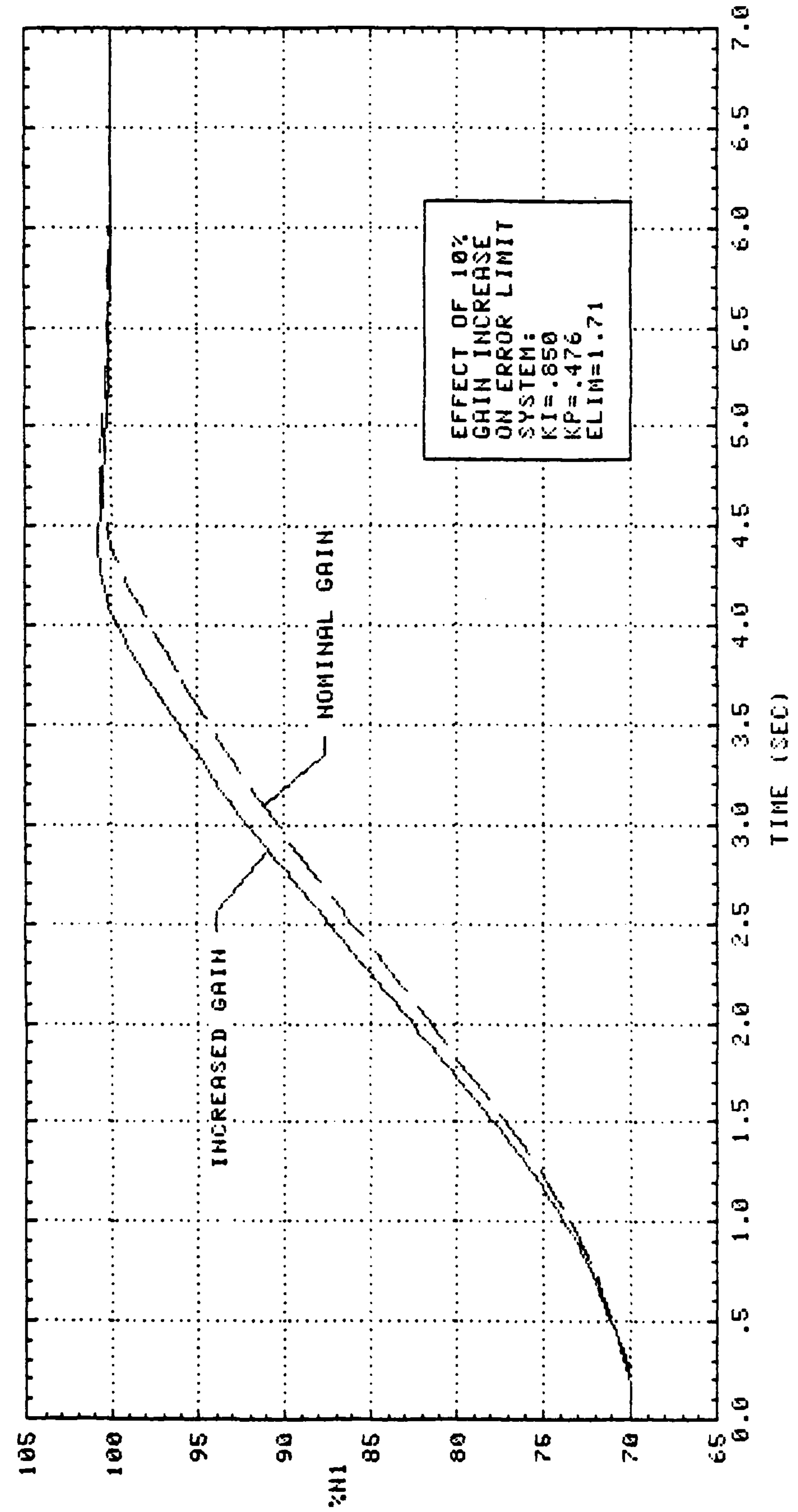
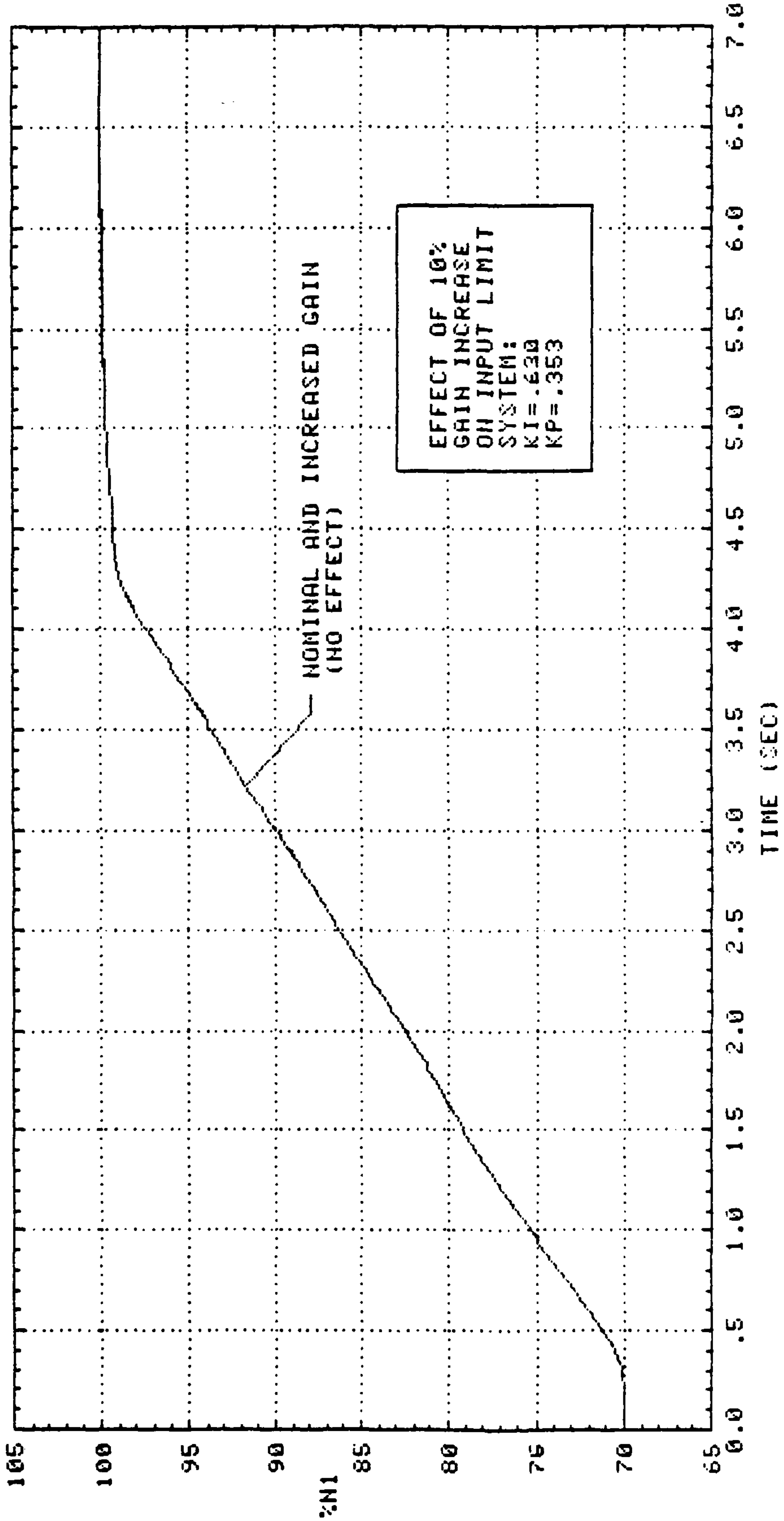

EFFECT OF 10%
GAIN INCREASE
ON ERROR LIMIT
SYSTEM:
KI=.850
KP=.476
ELIM=1.71
NOMINAL GAIN
INCREASED GAIN
%N1
105
100
95
90
85
80
75
70
65
0.0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
TIME (SEC)

Figure 31



EFFECT OF 10%
GAIN INCREASE
ON INPUT LIMIT
SYSTEM:
KI=.630
KP=.353
NOMINAL AND INCREASED GAIN
(NO EFFECT)
%N1
105
100
95
90
85
80
75
70
65
0.0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
TIME (SEC)

Figure 32

END

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